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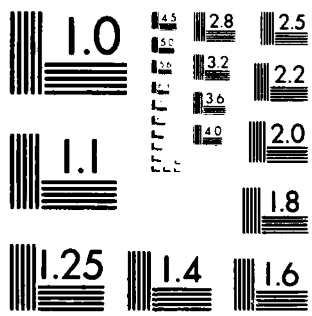

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Improving Conflict Alert Performance Using Moving Target Detector Data

Robert E. Lefferts

Prepared By
FAA Technical Center
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June 1982

Final Report

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16. Abstract

The feasibility of using measurements of aircraft radial velocity to improve the performance of the en route tracking algorithm in the present computational environment was examined. Radial velocity can be measured with equipment which is part of the Moving Target Detector (MTD) radar, a new type of search radar. Particular attention is paid in this report to the utilization of radial velocity in reducing speed and heading biases that occur during maneuvers.

The performance of the tracking and Conflict Alert algorithms is evaluated on five maneuver detection/observation methods, including the present method. Using both standard and track-oriented parameters yields a total of ten different analyses. A simplified simulation program produces quantitative data. Because the computational resources available for tracking algorithm modifications are limited, consideration of possible applications of radial velocity measurements is restricted to simple algorithm changes. Two aspects of performance are measured: the warning time to a hazardous situation, and the nuisance alert area, a recently developed measure of the false alarm performance of the algorithms.

It was concluded that the use of the radial velocity data was not justified in the present system given the limited computer resources available. The practicality of using radial velocity data in the more extensive system of the future is briefly considered.

17. Key Words
Conflict Alert Algorithm
Moving Target Detector
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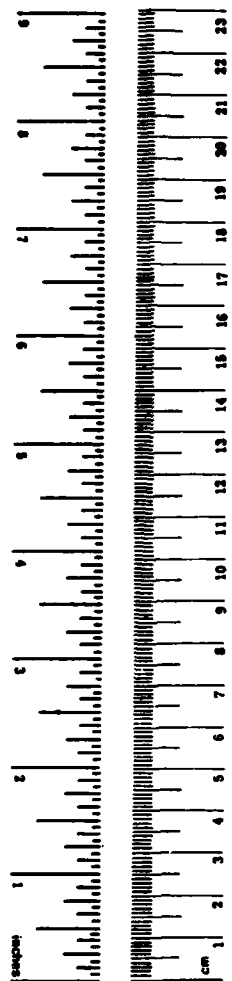
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

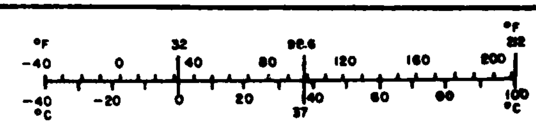
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



PREFACE

The author wishes to acknowledge the contributions of Daniel C. Penrith, of the Range, Programming and Analysis Branch, FAA Technical Center, who provided programming support; and James A. Shannon, of the En Route Branch, Systems Research and Development Service, who computed the initial positions used in the nuisance alert area simulations.

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EXECUTIVE SUMMARY

The Moving Target Detector (MTD), a new type of search radar detector, is capable of providing measurement of the radial velocity of a target by the Speed Interpolation Numbers (SIN's) generated in its information processing. Provisions could be made for the use of SIN's by the tracking algorithm if this w re found to be sufficiently valuable. The objective of this study was to determine if performance improvements in tracking resulting from such use of radial velocity data adequately justifies the transmission and manipulation of the data.

The evaluation was based on the performance of the Conflict Alert algorithm for a set of scenarios representative of operational conditions. A simulation program was developed to obtain quantitative performance data and was accurate for the purposes of this study. However, for functional simplicity, it did not include the operation of the tracking algorithm in a multisensor environment or the altitude-tracking logic. Since the computational resources available in the present system for tracking modifications are limited, consideration was restricted to simple algorithm changes requiring minimal computational resources for implementation.

It was determined that the only practical use that could be made of the SIN's under these conditions would be as a maneuver detector: large scan-to-scan differences would be interpreted as changes in radial velocity. This maneuver detection function is one currently performed with the track datum deviation.

Because some form of back-up maneuver detection must be provided for cases in which the MTD data is not available, a total of five maneuver detection options were considered: (1) a fixed search area (as presently used); (2) a dynamic search area; (3) a dynamic search area with a one-scan delay in the use of the maneuver smoothing parameters; (4) the MTD plus a dynamic search area, both with a one-scan delay; and (5) the MTD plus only the dynamic search area with a one-scan delay. The smoothing constants used when a maneuver was detected were considerably larger than the parameters presently in use in order to make the tracking algorithm more responsive. Also, the track-oriented smoothing feature was used to weight the cross-track deviation more heavily than the along-track deviation.

The performance of the tracking and Conflict Alert algorithms was evaluated with the five maneuver detection options and with the standard and track-oriented smoothing parameters, giving a total of ten different evaluation methods. The simulations were carried out assuming an optimistic value for the errors in the SIN's. Two aspects of performance were measured: the warning time to a hazardous situation, and the nuisance alert area, a recently developed measure of the false alarm performance of the algorithms.

In examining the results of the warning time tests, it was found that in almost all cases there was no significant difference in performance between the various maneuver detection options or between the results with standard or track-oriented smoothing. In only one of the four scenarios was an improvement in warning time for track-oriented smoothing judged to be significant. But even in such a case, the improvement in an operational environment would likely be only one or two radar scans. Further, the performance for this scenario was already completely acceptable using the standard parameter values. As a result, it was concluded on the basis of the warning time results that there were no significant differences that would justify any of the proposed changes in the tracking algorithm.

The nuisance alert area simulation results were more difficult to interpret. The nuisance alert area was reduced in three of the scenarios, but was significantly increased in one. Clearly, the single largest effect was due to the use of track-oriented smoothing; performance variations between maneuver detection options could not be considered particularly significant in most cases. By combining the nuisance alert area results using various assumed weighting factors, one overall measurement of performance could be developed (though, of course, if an operational environment differs from that represented by the weighting factors, the conclusions based on combined results would not be valid so this was not done).

If a significant number of cases in an operational environment corresponded to the second scenario in which an increase in the nuisance alert area occurred, then the number of false alarms might increase rather than decrease, as predicted with the combined results. The increase in this particular case was thought to have been caused by the substantial increase in the speed and heading errors for straight-line tracks, a penalty that must be accepted if track-oriented smoothing is to be used.

While the overall nuisance alert area performance was best when the MTD combined with the dynamic search area (both using one-scan delays) was used, the total performance of the dynamic search area with delay was insignificantly different. However, the increase in the nuisance alert area, and of speed and heading errors, for the second scenario was significantly less using the dynamic search area with delay than the increases observed with the other maneuver detection options. In addition, it was found that the nuisance alert area was significantly reduced by changing the size of the alert generation region in the Conflict Alert algorithm.

Since the choice between maneuver detection options was complicated by contradictory results, auxiliary factors were also considered. The dynamic search area with a one-scan delay is a trivial computational modification, while the combination of the dynamic search area with the MTD would have considerably higher computational and storage requirements. As a result, it was concluded that there is no justification for using the SIN's provided by the MTD in the present system, since the performance improvements that could be obtained using this data can be duplicated if far simpler modifications and parameter changes are made in the present system.

These results and conclusions apply only to the computationally limited environment of the present computer system. In the future, the operational environment will be considerably different as a result of the introduction of higher quality data from Mode S (formerly the Discrete Address Beacon System) and the essentially unlimited computational capacity that will be available with the new air traffic control computer being planned.

The question arose whether the MTD data would be useful then. Without knowing the operational accuracy of the SIN's or the performance of the tracking algorithm in the future environment, it was not possible to either eliminate the MTD data from consideration or demonstrate a specific requirement for this data. One point immediately obvious, though, was that with more accurate data and a more sophisticated algorithm, the need for the MTD data in the new system would have to be reexamined particularly if a data link from the target was available.

1. INTRODUCTION.

The Moving Target Detector (MTD) is a new type of search radar detector (references 1 and 2) that, in processing radar information, measures the radial velocity of targets according to a measure termed the "Speed Interpolation Number" (SIN). Such radial velocity data are considered of possible value in improving the performance of the National Airspace System (NAS) en route tracking algorithm. In particular, it is hoped that a practical mechanism for reducing the speed and heading biases, that develop during tracking of a maneuvering target, might be developed through comparison of scan-to-scan differences in SIN's. The objective of this study is to determine the degree of any such performance improvement in the present operational environment particularly the Conflict Alert algorithm (references 3 and 4), and whether that improvement would be a reasonable application of SIN's.

The emphasis in this report is on examining the interaction between the National Airspace System (NAS) en route tracking algorithm and the Conflict Alert algorithm, which uses the data provided by the tracking algorithm, rather than on the performance of the tracker per se. Some indications of the magnitude of the tracking improvements that might be observed were given in the preliminary report on the use of the MTD data in NAS tracking (reference 5). It was also noted in this report that the most likely practical use of the MTD would be as a maneuver detector to complement the maneuver detection capability provided by the search areas in the tracking process. Although other studies have examined the possibility of directly using the radial velocity in the tracking algorithm (references 6 through 10), this approach was not considered feasible in NAS at present. Note in the present study that although the MTD derives the radial velocity measurements from search or primary radar returns, the position measurements are always assumed to be derived from beacon reports. Identity and false target problems can thus be ignored.

Because the application of the MTD in the en route environment is still in the test and evaluation stage, it is necessary to base certain assumed characteristics of the MTD data on very limited samples of test data. For purposes of the present study, an optimistic value for the standard deviation of the Speed Interpolation Numbers is used. Thus, if the actual performance of the MTD is significantly different, the results obtained are not valid. Further, the simulations are performed using only a limited set of parameter values and no attempt is made to optimize the results.

2. TECHNICAL DETAILS OF THE SIMULATION PROCESS.

The approach taken in this study is based on a simplified simulation of the NAS en route tracking algorithm. A general description of the technical aspects of the simulation is given in the following sections.

2.1 SELECTION OF TRACKING SIMULATION BASELINE RESULTS.

Evaluation of any proposed change to a system requires some form of baseline against which to judge the impact of the modification. In the case of the performance of the NAS en route tracking algorithm there are several sources that could be used as a partial baseline for evaluating tracking performance

(references 11 and 12). However, the results found in these sources were obtained using a program that simulated the operations of both the Multiple Radar Data Processing function (MRDP) (reference 13), and the Automatic Tracking (AT) functions in the NAS operational program. In order to get comparable results to evaluate the use of MTD data in tracking, it would be necessary to use the same simulation program, with modification, as is used to obtain the baseline. While this would be desirable for accuracy, modification of this simulation would be an undertaking of such magnitude as to prohibit completion of this study within a reasonable time period.

In addition to the problem of modifying the simulation program, there are those of actually performing the simulations required and then using special purpose data reduction programs to determine the results. It would also be necessary, in order to obtain data on the Conflict Alert function, to create a library of scenarios in which conflicts are generated. For these reasons, it is determined that the use of a simulation program duplicating the NAS operational program in great detail is not practical, and that an alternative approach is necessary.

The approach taken in this study is to use a simulation of a fixed-time interval α-β tracker without considering operation in a multiple-site environment. This greatly simplifies the programming and data reduction required in the evaluation. Although such simplification does not allow evaluation of aspects of the MRDP to AT interaction such as multiple-radar sites or asynchronous operation of the sensor and tracker, it does provide a realistic environment for evaluating basic changes in the structure of the tracker, such as those involved in the use of the MTD data. If results obtained using such a highly simplified approach are favorable, further testing in a more elaborate test environment is justified.

Since a different program is used as the test environment, the tracking results that might have been considered as the baseline are not applicable. A new baseline is constructed specifically for this task, using a series of simulations involving straightline and maneuvering targets which yield sufficient data for analysis of the performance of the Conflict Alert algorithm. Various performance statistics are gathered during the simulations, and a range of conditions are considered in order to obtain an indication of the sensitivity of the results to the various conditions.

One important point which should be remembered throughout the discussion of the simulation results presented in this report is that the same sequence of random numbers is used for every simulation. As a consequence, the simulation results can be compared directly with one another without the need for a statistical hypothesis test. Any differences observed are solely a function of the deterministic changes in the simulation environment and not a result of random replication of a different experiment. The use of this technique results in a considerable simplification in the interpretation of the results. In many cases, it is found that the differences in the performance measurements for different formulations of the tracking algorithm are so insignificant that these differences would most likely not be detected using hypothesis tests.

2.2 DESCRIPTION OF SIMPLIFIED TRACKING ALGORITHM.

The simulation program used in this study is a simplified version of the NAS bimodal tracking algorithm (reference 3) with a fixed time interval and using a single radar site that observes all tracks synchronously. In addition, the entire tracking simulation takes place in a common Cartesian coordinate system so that the altitude tracking algorithm and the problems inherent in the altitude tracker (reference 14) can be ignored. Since the multiple radar site environment is not considered, the technique of stereographic projection (reference 15) used to map data from various radar sites onto a common coordinate system, can likewise be disregarded.

The use of a single radar site results in considerable simplification of the correlation process (reference 13) used to associate radar surveillance data with a particular track. While the simulation program in this study does not model the problems and conditions encountered in a multiple radar site environment, it does provide a sufficiently realistic test bed for evaluation of basic changes in the NAS tracking algorithm. The simplified tracking just discussed is described in the following sections.

2.2.1 Isotropic Tracking Algorithm.

The tracking algorithm of interest in this report is the NAS en route tracking algorithm. It is a bimodal tracker, meaning the weighting parameters can take two different sets of nonzero values depending on the deviation between the measured and predicted positions.

At any epoch (scan) k, the tracking algorithm is specified by the following equations:

$$\vec{X}_s(k)=\vec{X}_p(k)+\alpha\Delta r(k) \tag{1}$$

$$\vec{V}_s(k)=\vec{V}_s(k-1)+\beta\Delta r(k)/T \tag{2}$$

$$\vec{X}_p(k+1)=\vec{X}_s(k)+T\ \vec{V}_s(k) \tag{3}$$

$$\Delta\vec{r}(k)=\vec{X}_m(k)-\vec{X}_p(k) \tag{4}$$

where:

$\vec{X}_s(k)$ = Estimated position

$\vec{V}_s(k)$ = Estimated velocity

$\vec{X}_p(k)$ = Predicted position

$\Delta\vec{r}(k)$ = Track datum deviation

α = Position smoothing constant

β = Velocity smoothing constant

$\vec{X}_m(k)$ = Position of the radar measurement

T = Scan time or measurement interval.

When the problems of operation in a multiple radar site environment and asynchronous operation of the sensor with respect to the tracking algorithm are not considered, it can be assumed that the measurement data $\vec{X}_m$, are available at a constant rate specified by the time interval, T.

The track datum deviation, $\Delta\vec{r}(k)$, is presently used as the basis for choosing the value of the smoothing constants. The decision process for the smoothing constants can be defined as follows:

$$\alpha = \begin{cases} \alpha_S & \Delta\vec{r} \in A_S \\ \alpha_L & \Delta\vec{r} \in A_L \\ 0 & \Delta\vec{r} \notin A_L \end{cases} \qquad \text{where } \alpha_S \leq \alpha_L \tag{5}$$

$$\beta = \begin{cases} \beta_S & \Delta\vec{r} \in A_S \\ \beta_L & \Delta\vec{r} \in A_L \\ 0 & \Delta\vec{r} \notin A_L \end{cases} \qquad \text{where } \beta_S \leq \beta_L \tag{6}$$

where A_S and A_L are referred to as the small and large search areas, respectively. It should be noted that A_S is contained within A_L. The search areas used in practice vary in size and shape according to the type of data used and the magnitude of the track datum deviation (e.g., see reference 2). The smoothing constants used in the small search area are chosen to given a high degree of noise reduction (via relatively small values of α and β), while the smoothing constants used in the large search areas are chosen on the basis of the transient response characteristics (thus implying larger values of α and β). Various criteria can be the basis for choosing the smoothing constants in either search area, but it is usually intended that the small search area smoothing constants be used with straight-line tracks, and the large search area ones with maneuvering tracks.

The need for multiple smoothing constants arises because smoothing constants that give a high degree of noise reduction are not satisfactory for following maneuvering targets. When a target begins to maneuver, a bias that is due to the assumption of a constant velocity straight-line track develops in the predicted position. In most cases this bias becomes large enough to cause the tracker to switch to the larger smoothing constants in the large search area, which removes much of the bias and causes the tracker to revert to the use of the small search area smoothing constants.

The magnitude of the bias, observed both in position and velocity, is of considerable interest because advanced air traffic control features, such as Conflict Alert, require accurate estimates of future positions in order to operate properly. Bias errors can cause major problems in the operation of such features. As a result of the alternation between sets of smoothing constants, this tracking algorithm is referred to as a bimodal tracker.

The sample moments used for the comparison of the tracking simulations are obtained in the following manner. The sensor measurements are assumed to consist of the sequences $\{\rho_T(k)\}$ and $\{\theta_T(k)\}$, where $\rho_T(k)$ and $\theta_T(k)$ are the true range and

azimuth, respectively, of the target at time epoch, k. In the simulation program, the sensor measurements are corrupted by errors, $\Delta\rho(k)$ and $\Delta\theta(k)$, generated in such a manner that each sequence $\{\Delta\rho(k)\}$ and $\{\Delta\theta(k)\}$ is white and stochastically independent of the other. The simulated track data sequences $\{\rho_T(k)+\Delta\rho(k)\}$ and $\{\theta_T(k)+\Delta\theta(k)\}$ are transformed to a Cartesian coordinate system to give the simulated radar measurement sequence $\{\hat{X}_m(k)\}$ which is input to a digital filter defined by equations (1) to (4).

In order to determine what constitutes the typical behavior of the tracking algorithm, the experiment of generating a random track data sequence for use as input to the tracking algorithm is repeated to generate an ensemble of responses, each of which is stochastically independent of the others. At each epoch, k, there are various samp'e moments (ensemble averages) that can be used to characterize the performance of the tracking algorithm for the true track being using as the basis for the simulation.

For example, for each of the N-simulated radar measurement sequences, the output of the digital filter consists of the sequences:

$$\{X_s(k, i), Y_s(k, i)\}$$

$$\{V_x(k, i), V_y(k, i)\}$$

$$\{X_p(k, i), Y_p(k, i)\}$$

where X_s, Y_s = estimated position

V_x, V_y = estimated velocity components

X_p, Y_p = predicted position components,

and $i=1,\ldots,N$, where i is the population index and N is the sample size. Denoting the true position and velocity of the target as $\{X_T(k), Y_T(k)\}$, $\{V_{Tx}(k), V_{Ty}(k)\}$, respectively, one sample moment that might be of interest in this study is the mean heading error, which is defined as:

$$\theta(k) = \frac{1}{N}\sum_{i=1}^{N}\left[\tan^{-1}(V_x(k, i)/V_y(k, i)) - \tan^{-1}(V_{Tx}(k)/V_{Ty}(k))\right]. \qquad (7)$$

It is quite obvious that there are other performance measures that could be developed based on the simulution output (e.g., position and velocity errors). For the purpose of this study, however, the primary emphasis is placed on the measures that describe the performance of the Conflict Alert algorithm, rather than the tracking algorithm per se, although some limited examples of the tracking performance are given.

2.2.2 Nonisotropic Smoothing.

In the tracking algorithm just specified, the smoothing and prediction process operates uniformly in both dimensions. This is not required to be the case. For target returns falling in the large search area, indicating a maneuvering target, it may be desirable to process the data in a slightly different manner.

Since the ultimate objective in the use of the MTD data is to reduce the bias observed in the output of the tracking algorithm during maneuvers, thereby improving the performance of the Conflict Alert function, it is necessary to examine the tracking algorithm to determine how this additional information can be incorporated into the tracking process. It is believed, for reasons stated later, that the most obvious manner in which to utilize the MTD data is as a switching mechanism for selection between the tracking algorithm's track-oriented or nonisotropic smoothing features. The latter is that in which the crosstrack (lateral) deviations are weighted differently than the along-track (longitudinal) deviations (i.e., the coordinate system used for smoothing is rotated so as to be aligned with the estimated velocity).

Naturally, the objective in track-oriented smoothing is to use lateral smoothing constants that are significantly larger than the longitudinal smoothing constants. This causes a more rapid rotation of the heading, making the tracking algorithm more responsive to maneuvering targets. The numerical computations required to perform track-oriented smoothing are already part of the tracking specification, but since the lateral and longitudinal smoothing parameters are equally weighted, this capability is not presently being used.

The equations specifying the computations performed for track-oriented smoothing are given by (reference 3)

$$D_x'(k) = \frac{D_x(k)V_x(k-1) + D_y(k)V_y(k-1)}{V_x^2(k-1) + V_y^2(k-1)} \tag{8}$$

$$D_y'(k) = \frac{D_x(k)V_y(k-1) - D_y(k)V_x(k-1)}{V_x^2(k-1) + V_y^2(k-1)} \tag{9}$$

$$X_s(k) = X_p(k) + b_1\, D_x'(k)\, V_x(k-1) + b_2\, D_y'(k)\, V_y(k-1) \tag{10}$$

$$Y_s(k) = Y_p(k) + b_1\, D_x'(k)\, V_y(k-1) - b_2\, D_y'(k)\, V_x(k-1) \tag{11}$$

$$V_x(k) = V_x(k-1) + \beta_1\, D_x'(k)\, V_x(k-1)/T + \beta_2\, D_y'(k)\, V_y(k-1)/T \tag{12}$$

$$V_y(k) = V_y(k-1) + \beta_1\, D_x'(k)\, V_y(k-1)/T - \beta_2\, D_y'(k)\, V_x(k-1)/T \tag{13}$$

where all equations have now been expressed in terms of the appropriate vector components and

b_1 = longitudinal position smoothing constants

b_2 = lateral position smoothing constants

β_1 = longitudinal velocity smoothing constants

β_2 = lateral velocity smoothing constants,

$D_x(k)$, $D_y(k)$ = track datum deviation components of $\Delta\vec{r}(k)$.

The computations required to resolve the track datum deviation into lateral and longitudinal components are performed by using the velocity components to compute the required trigonometric functions because the computational resources needed for (8) to (13) are much less when formulated in this manner. Note that the track-oriented smoothing feature is only intended to be used for returns in the large search area; i.e., the function of α_L and β_L is now done using b_1, b_2, β_1 and β_2, with the small search area processing being specified by (1) to (4), as previously given.

2.2.3 Track Datum Deviation Components For Maneuvering Targets.

The analysis below illustrates the differences in the track datum deviation when resolved into lateral and longitudinal components. The notation used in this section is separate from that used elsewhere.

An illustration of a track-oriented coordinate system is given in figure 1. Consider a turn starting at scan one in which the heading changes at a constant rate ω. If the predicted position for scan two is based on the assumption of a straight-line constant velocity, then the predicted position differs from the true position (ignoring any measurement errors that might occur). In the noiseless case, the track datum deviation resulting from the violation of the assumption used to calculate the predicted position is $\vec{D}$ (note that in this case $\vec{D}$ is a bias error).

It would be logical to give a larger weight to the larger deviation. A nonmilitary airplane can only accelerate or decelerate to a very limited degree along its track. Across the track, however, the change can be significantly greater. In order to determine the magnitude of the weighting factors, the ratio of the lateral to longitudinal deviations in a coordinate aligned with the true velocity is determined. If it is assumed that the target turns at a constant rate, the components of the deviation in the original coordinate system are

$$D_x = X_2' - X_2$$

$$D_y = Y_2' - Y_2 \qquad (14)$$

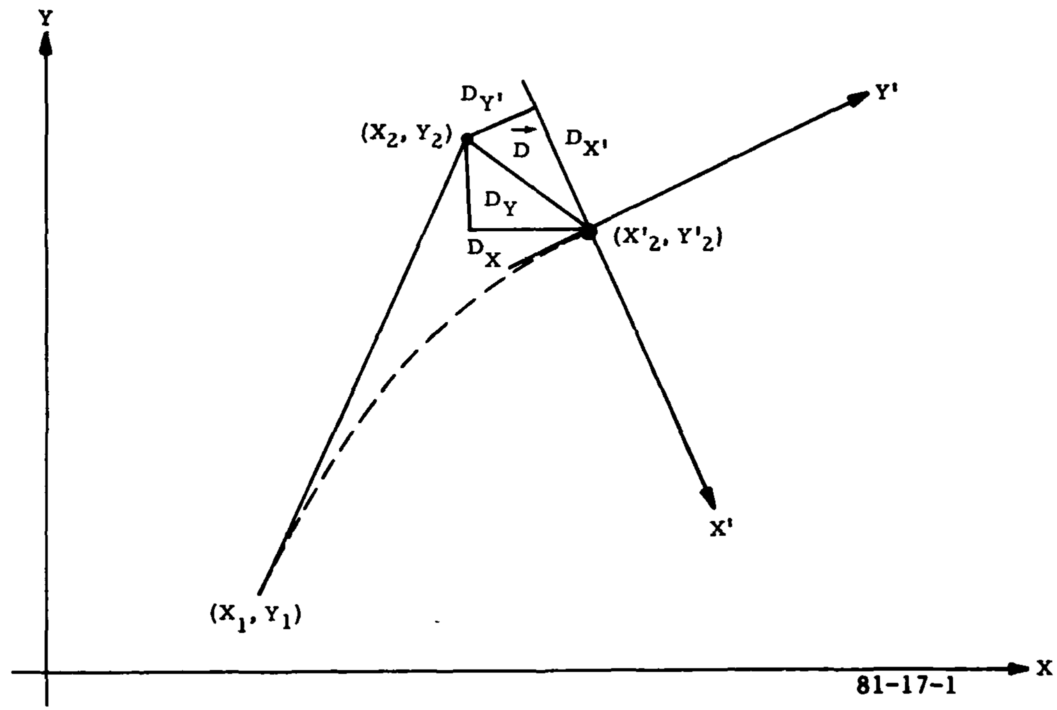


FIGURE 1. ILLUSTRATION OF RESOLUTION OF TRACK DATUM DEVIATION INTO VELOCITY-ORIENTED COORDINATE SYSTEM

where

$$X_2' = X_1 - (V \cos \theta_2 - V \cos \theta_1)/\omega$$

$$Y_2' = Y_1 + (V \sin \theta_2 - V \sin \theta_1)/\omega \tag{15}$$

$$X_2 = X_1 + VT \sin \theta_1$$

$$Y_2 = Y_1 + VT \cos \theta_1$$

X_1, Y_1, θ_1 = initial position and heading

$\theta_2 = \theta_1 + \omega T$ final heading

V = speed

T = scan time

ω = heading change rate.

The ratio of the lateral to longitudinal deviations at the second scan is

$$r = D_x'/D_y' \tag{16}$$

or, in terms of the deviations in the coordinate system used for tracking,

$$r = \frac{D_x \cos \theta_2 - D_y \sin \theta_2}{D_x \sin \theta_2 + D_y \cos \theta_2} \tag{17}$$

and, after substituting (15) into (14) and simplifying,

$$r = \frac{\cos (\omega T) + \omega T \sin (\omega T) - 1}{\sin (\omega T) - \omega T \cos (\omega T)} \tag{18}$$

This is independent of the position, velocity, and orientation in the original coordinate system, as would be expected.

The deviation ratio, r, is plotted in figure 2 as a function of the heading change per scan. The actual values of the lateral and longitudinal deviations observed for a 200-knot target are given in figure 3. Surprisingly, the deviation ratio decreases as the turn rate increases, but, as would be expected, the actual deviations increase, up to a point, as the turn rate increases. Since targets that change heading at low turn rates are not a problem (because of the small deviations), the ratio of the deviations alone does not provide a performance measurement specifying the circumstances in which a large heading bias is likely to develop.

The highest heading bias errors are found in situations where the turn rate is on the order of 3°/second or $\omega T \approx 30$, and, in this case, the deviation ratio is only 2.7. Thus, a large value of the lateral-to-longitudinal deviation ratio is not indicative of a situation in which a large heading error will arise. Quite the contrary; in situations in which large heading bias errors are found, the deviation ratio will probably be in the range of 1.5 to 6.

One obvious means to reduce the heading bias error is to weight the lateral deviation by the deviation ratio for the particular value of ωT at which the target is maneuvering. It is easily seen, however, that even for small values of the longitudinal velocity smoothing constant, the lateral smoothing constant would be significantly larger. As a result, even small measurement errors would be considerably magnified, and the use of a lateral smoothing constant in proportion to the deviation ratio would cause, for this reason, serious perturbations in the tracking algorithm.

If the data available for use by the tracking algorithm were perfect, then the smoothing constants dictated by the deviation ratio could be used. However, in reality, smoothing parameters determined in this manner would result in unstable operation of the tracking filter due to the noisy data. Consequently, the deviation ratio can be considered an upper bound on the lateral-to-longitudinal smoothing parameter ratio which effectively limits the amount of crosstrack smoothing that can be applied and, hence, the reduction in the heading bias observed.

2.2.4 Maneuver Detection Options And Applications Of MTD Data.

The tracking algorithm has two modes of operation: one for straight-line tracks and the other for tracking maneuvering targets. The choice of mode of operation is contingent upon on the type of search area of the track in which the surveillance datum is located. The mode of operation of the tracking algorithm is, then, a function of the magnitude of the track datum deviation if the search areas are circular, as are in all cases in this report. For the baseline tracking algorithm, the search areas are fixed in size for reasons of computational simplicity. There is some evidence that a dynamically varying search area is more advantageous (references 16 through 18), since the size of the search area adapts to the characteristics of the radar measurement errors throughout the coverage area of the sensor. Regardless of whether the search area size is fixed or dynamic, the primary function is still the same: the detection of maneuvers.

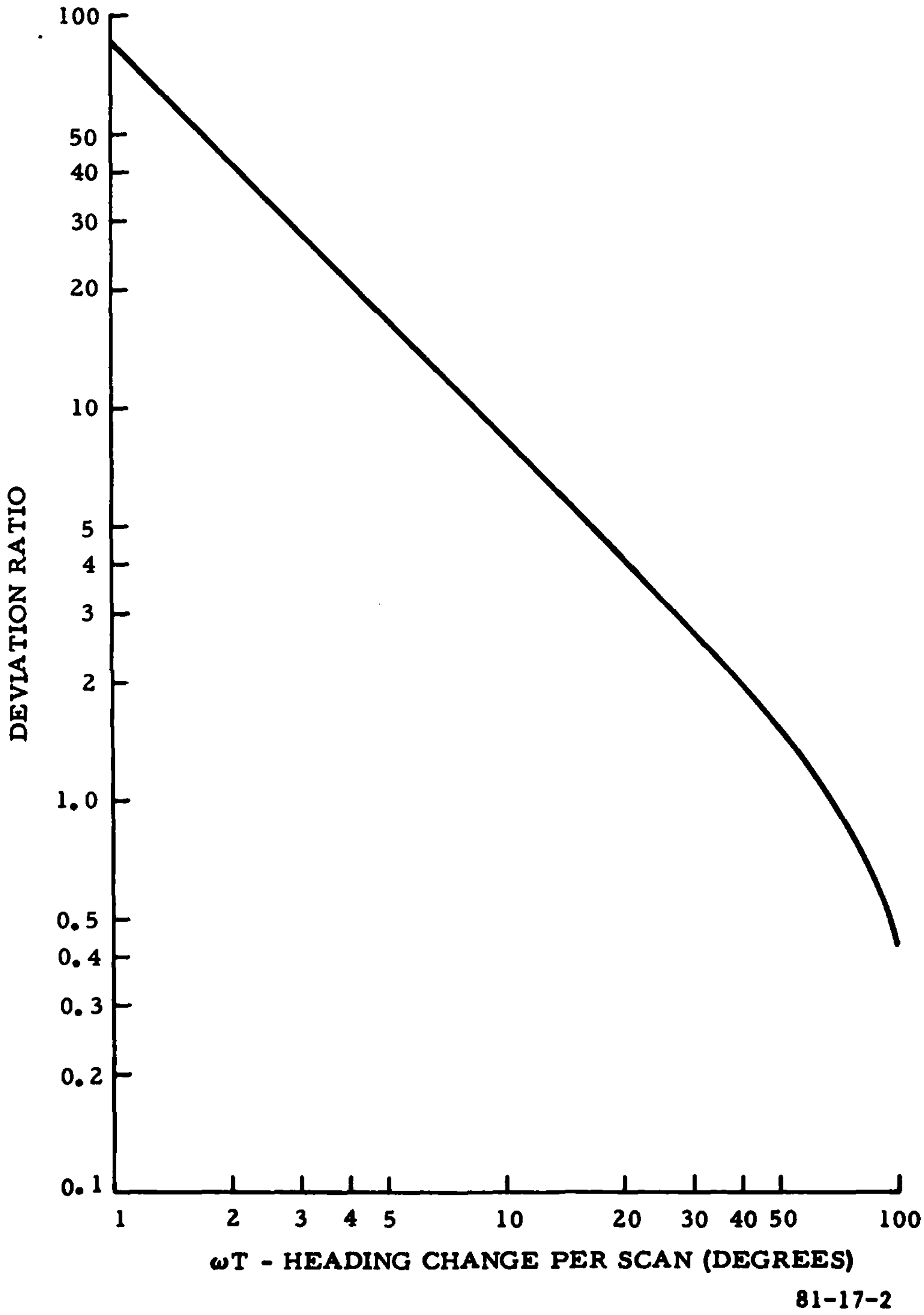


FIGURE 2. RATIO OF LATERAL TO LONGITUDINAL DEVIATIONS

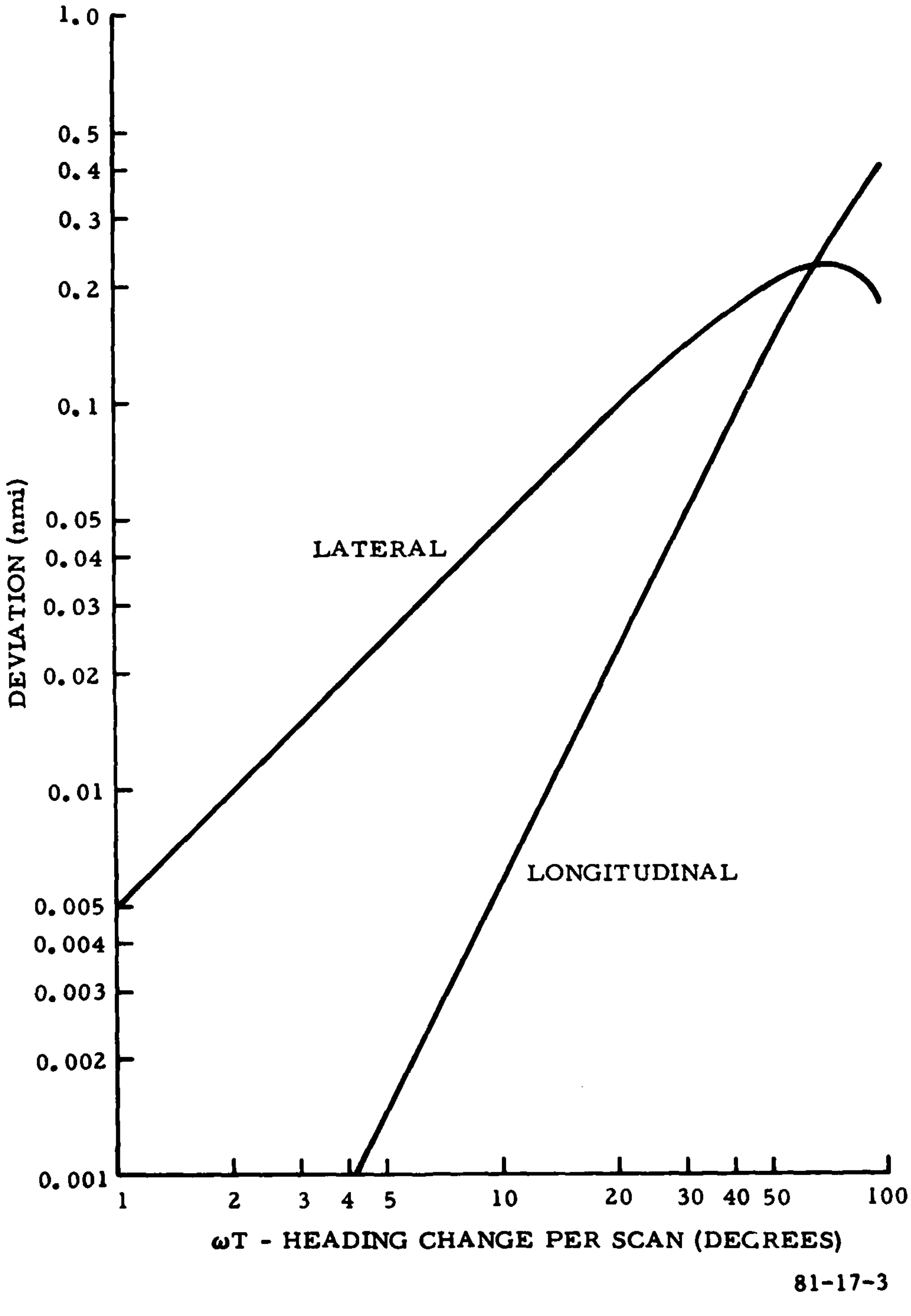


FIGURE 3. LATERAL AND LONGITUDINAL DEVIATIONS FOR 200-KNOT TARGET

The SIN's supplied by the MTD may also be used as the basis for the detection of maneuvers. Since the radial component of target velocity varies according to the type of maneuver and the aspect of the track with respect to the radar, the SIN also varies accordingly. As a result, the scan-to-scan changes in the radial velocity (or, equivalently, the SIN) may be used as an indication of whether or not a target is maneuvering. If a maneuver is detected this information can then be used to switch to different smoothing constants. It should be noted, however, that even for straight-line tracks, the radial velocity component changes but, hopefully, very slowly compared to a maneuvering target.

In some cases, such as straight-line tracks close to the radar, the magnitude of the change in the radial velocity component can be as large as that observed for a maneuvering target at a greater range. For this reason, it may be necessary to prohibit the use of MTD data within a specific radar range. This critical range should be chosen so that for targets at greater distances, it would be possible to accurately discriminate between and maneuvering and nonmaneuvering targets. Of course, when errors in the velocity measurements are considered, it may be necessary to increase the critical range to compensate for these errors or, to use the estimated heading to limit consideration to tracks in which the major component is in the radial — rather than the tangential — direction.

As noted in previous studies (references 6 through 10) it may also be possible to use the radial velocity directly in the tracking algorithm, if it is found to be sufficiently accurate. In this case, it would be necessary to resolve the tracker velocity into two orthogonal components: the estimated radial component and the estimated tangential component. Once the estimated velocity has been resolved into these two components, several approaches are possible, all of which basically involve replacing the estimated radial velocity with the measured radial velocity (or some weighted combination of both.) Whatever the case, the velocity components must be rotated back into the original Cartesian master plane and then used to calculate the predicted position. Considering the computational complexity of actually using the measured radial velocity, it may be determined that even if this approach does have some performance advantage, it would not be practical for implementation.

However, the question of whether radial velocity is sufficiently accurate to be used directly in the tracking algorithm has not yet been examined. If the data accuracy is not sufficient for use in a threshold situation (i.e., one in which the MTD data is used to switch the smoothing constants), then it will not be sufficiently accurate to be used directly in the tracking algorithm. For this reason, only an approach using a threshold for parameter changes is examined in this report.

In the case of a bimodal tracking algorithm there is the question of what should be done the first time a maneuver is detected. Several previous studies (references 12 and 19 through 21) have shown that there is some advantage in using different smoothing parameters for the first large search area return instead of the normal set of smoothing parameters used in the large search area. The justification for giving special consideration to the first large search area return is the possibility that the return may be spurious.

False radar returns can arise in many different ways, depending on the type of radar being used. Search radar can have returns from weather clutter rather than from aircraft, and beacon systems can receive false returns due to reflections. In the tracking process, beacon systems can also incorrectly use valid beacon returns from targets using the same beacon code (or nondiscrete codes). In the case of a straight-line track, even for a valid large search area return for the target of interest, the use of the large search area smoothing constants may result in an undesirable track perturbation. For these reasons, there is considerable merit in treating the first large search area return in a different manner than subsequent ones.

The alternatives that might be considered for treatment of the first large search area return range from discarding the return altogether (because it is "probably" a false return) to applying a very high weighting factor (because it is "probably" the start of a maneuver). The evaluation of these alternatives is dependent, of course, on the degree to which a large search area return is thought to represent a maneuvering target or is thought to represent a false return and the penalties associated with an incorrect decision. Generally, the use of an erroneous data point or application of the large search area smoothing constants to a straight-line track are viewed as more serious errors than the very slightly higher bias errors that result from waiting one scan to apply the large search area smoothing constants.

Results that are presented in a later section illustrate the specific performance penalities associated with the delay in the use of the large search area smoothing constants in the case of a straight-line track. For the purpose of this study, a delay in the use of the small search area smoothing constants indicates that the first large search area return is weighted with the small search area smoothing constants so that no data is ever discarded.

There are several options, then, for developing a switching mechanism for selection between alternate sets of smoothing constants. The fixed search area, the dynamic search area, and the MTD switch represent distinctly different approaches to the same problem. Because the MTD switching mechanism cannot detect as maneuvers those turns that yield certain radial velocity differences, it cannot be used alone. A secondary switching mechanism must be available as a backup. The two mechanisms would be competitive, in the sense that both would perform the same function, and complementary, in the sense that one may detect a maneuver before the other. Combined use of two might give better performance than any single technique.

The dynamic search area is the better choice for the backup function because, unlike the fixed search area, it is an adaptive technique that guarantees a specified level of performance throughout the coverage area of the sensor. The use of the MTD switch with a fixed search area backup would result in significantly larger biases developing in those cases in which the MTD threshold was not exceeded and it is necessary to rely on the fixed search area to switch the smoothing constants.

In addition to the question of which maneuver detection option or combination of options would be best, there is also the question of whether or not the smoothing constants for maneuvers are to be used on the first scan detecting a maneuver. For the purposes of this study, the five options given below are chosen for evaluation:

a. Fixed search areas

b. Dynamic search areas

c. Dynamic search areas with a one-scan delay

d. MTD with a one-scan delay combined with dynamic search areas with a one-scan delay

e. MTD with no delay combined with dynamic search areas with a one-scan delay.

These maneuver detection options are believed to be the most reasonable approaches to the detection of maneuvers. In the last two cases, the options are assumed to operate independently of one another with the exception in the fourth case that if both techniques detect a maneuver at the same time, no delay is used. The characteristics of the MTD important for maneuver detection are discussed in the following two sections.

2.3 DETERMINISTIC ANALYSIS OF THE MOVING TARGET DETECTOR DATA.

Since the variation of the radial component of velocity differs according to the type of maneuver and the aspect of the track with respect to the radar, an analysis is performed to show how the radial velocity changes in various situations. Comparing the changes to the radial velocity (with the expected errors) for each scan gives an indication of whether or not maneuvers can be detected. It should be noted, however, that even for straight-line tracks, the radial velocity component changes but hopefully very slowly compared to a maneuvering target.

In some cases, such as that of a straight-line track close to the radar, the magnitude of the change in the radial velocity component may be as large as that observed for a maneuvering target at a greater range. For this reason, it may be necessary to prohibit the use of MTD data within a certain critical range from the radar. The critical range would be chosen so that for targets at greater distances it would be possible to accurately discriminate between straight-line tracks and maneuvering targets. Of course, when errors in the velocity measurements are considered, it may be necessary to increase the critical range to compensate for them.

To evaluate the feasibility of using the MTD data as a switch to change the smoothing constants, the expected scan-to-scan change in the SIN is evaluated for various situations. It is found that even for straight-line tracks there are certain situations in which large scan-to-scan differences are noted in the SIN, while for maneuvering targets there are certain situations in which the scan-to-scan differences are very small. These cases do not appear to the tracker to be turns. In order to quantify these results, an analysis is made of the SIN differences that are observed for a particular geometry, illustrated in figure 4. From this geometry it is easily seen that the radial velocity, which is the velocity component measured by the MTD, is given by

$$Vr_1 = |V| \cos \theta, \tag{19}$$

while the radial velocity at the second scan, which can be derived using the vector dot product, is

$$Vr_2 = (V_x(t_2)X_2 + V_y(t_2)Y_2)/\rho_2 \tag{20}$$

where

$$\rho_2 = \sqrt{X_2^2 + Y_2^2} \tag{21}$$

and X_2 and Y_2 are the Cartesian positions on the second scan. If the target is moving in a straight line,

$$\begin{aligned} V_x(t_2) &= V_x(t_1) \\ V_y(t_2) &= V_y(t_1) \\ X_2 &= X_1 + \Delta T\, V_x(t_1) \\ Y_2 &= Y_1 + \Delta T\, V_x(t_1), \end{aligned} \tag{22}$$

while in the case of a maneuvering target in which the heading changes at a constant rate of change, ω, the new position can be calculated by integrating the parametric equations of motion to give

$$\begin{aligned} X_2 &= X_1 - (V_y(t_2) - V_y(t_1))/\omega \\ Y_2 &= Y_1 + (V_x(t_2) - V_x(t_1))/\omega \end{aligned} \tag{23}$$

where

$$\begin{aligned} V_x(t_2) &= |V| \sin(\theta_1 + \Delta T\omega) \\ V_y(t_2) &= |V| \cos(\theta_1 + \Delta T\omega), \end{aligned} \tag{24}$$

θ is the heading on the first scan, and $|V|$ is the speed that is assumed to be constant. Substituting (23) and (24) into (20) and (21) gives the radial velocity of the target on the second scan, assuming the target dynamics can be represented by a constant rate of heading change turn. In all cases in this study a scan time of 10 seconds was assumed.

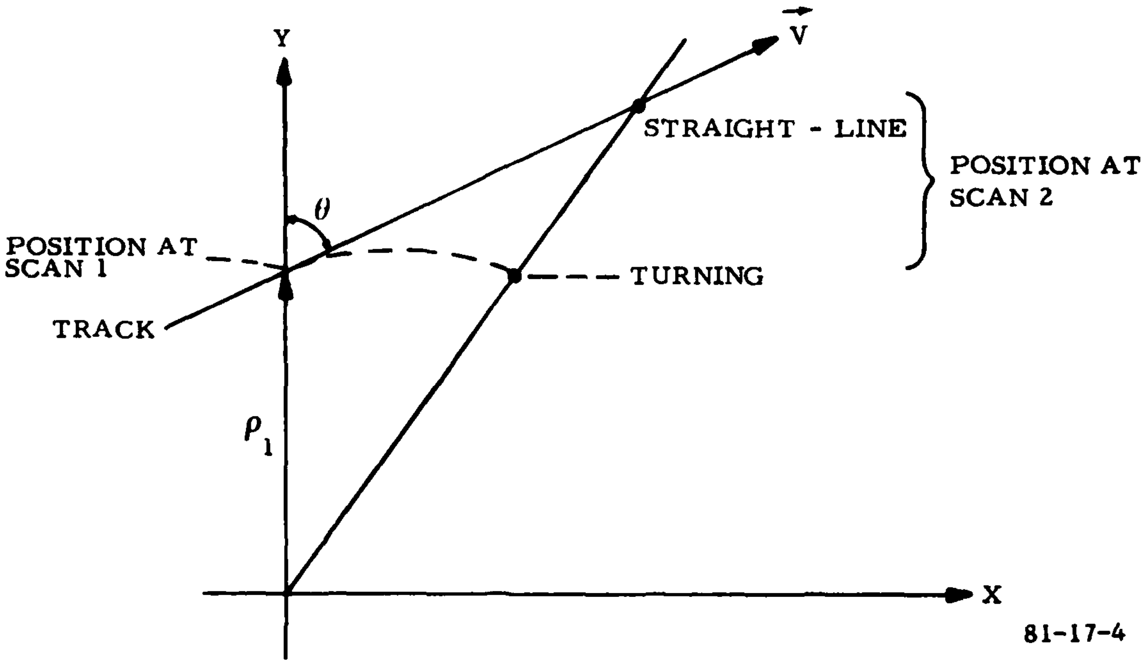


FIGURE 4. ILLUSTRATION OF SCENARIO USED FOR CALCULATION OF THE SCAN-TO-SCAN DIFFERENCES IN THE SPEED INTERPOLATION NUMBER

Once the radial velocity at each scan has been calculated, the SIN can be calculated. Since the MTD is a digital form of Moving Target Indicator, it has the usual characteristics of this form of detector: periodic nulls occur in the velocity response and at velocities that are integer multiples of the "blind speed." Mathematically, the radial velocity is measured modulo the blind speed, and the resulting velocity is scaled according to the bits available to represent the result. For example, in the MTD six bits are used, without sign, so that the SIN is related to the radial velocity by the relationship

$$I = 64.0 \text{ MOD } (|V_r|, V_b)/V_b \tag{25}$$

where V_b is the blind speed. The absolute value of the radial velocity is used to eliminate problems at the point where the radial velocity changes sign. It is assumed that the conversion to an integer number is performed by truncation so that $0 \leq I \leq 63$. Naturally, it is implicit in this equation that there are no computational errors or noisy measurements, which is, of course, never the case in practical situations. Errors are introduced due to random noise and from computational errors in the analog-to-digital conversion process. Since two different sampling frequencies are used in the MTD, there are also two blind speeds, so that in most cases two SIN are received for a target on each scan. Of course, it is possible that in some cases the signal strength will be sufficiently weak so that only one SIN will be received on a given scan, or that the target will not be detected at all. This possibility though, will not be considered for the moment.

Because the radial velocity is measured modulo the blind speed, care must be taken in the interpretation of SIN differences. Very large jumps may not represent maneuvers at all, but may simply be changes in the radial velocity, which cause a crossing of the blind speed. For this reason, the rule is developed that the maximum difference in the SIN that will be considered realistic will be 32, and any larger differences will be considered as a crossing of the blind speed and interpreted in the opposite sense (i.e., a circular interpretation corresponding to the case where angular differences are limited to a maximum of 180°). For example, if the SIN for a particular blind speed on two successive scans are 1 and 57, it is interpreted as a decrease of 8 rather than an increase of 56. It is more reasonable to interpret the change in a manner that indicates the least acceleration.

In order to determine the magnitude of the differences that would be observed in practice, the SIN differences for the geometry illustrated in figure 4 are computed in a deterministic manner, using the interpretation described above. Since the intended use of these differences is to switch the smoothing constants, the sign of the difference is of no consequence, and only the absolute value of the difference is considered. In addition, because there are two blind speeds and turn detection is desired, the maximum of the two differences is used when they are interpreted in the manner described above.

In order to consider all reasonable situations, the parameters in figure 4 are varied over a wide range, and a histogram of the maximum differences is computed. The parameters are varied in the following manner using standard notation for starting value, increment value, and ending value:

$$\theta = 0\ (10)\ 90 \text{ degrees}$$

$$V = 100\ (50)\ 550 \text{ knots}$$

$$\rho = 10\ (10)\ 170 \text{ nmi}$$

All combinations are considered to specify the conditions of the first scan, as both are straight-line and maneuvering targets. In the case of the maneuvering targets, it is assumed that the heading changed at a constant rate, ω, where (reference 24)

$$\omega = g \tan(\phi)/V, \tag{26}$$

g = acceleration of gravity, and ϕ is the bank angle (taken as 30°). The turn rate is limited to a maximum value of 3°/second which applies at speeds less than about 210 knots.

The results of these calculations for both straight-line and maneuvering targets are given in figure 5 in terms of the cumulative distribution function of the maximum value of the differences. As would be expected, the straight-line tracks produce a large number of low differences, while the maneuvering targets produce a large number of high differences. In order to make use of the SIN differences, it would be necessary to set a threshold that would be used to separate straight-line from maneuvering targets. However, it is apparent from figure 5 that even at relatively low maximum differences there are a number of turning tracks that would be missed. Conversely, even at relatively high maximum differences there are a significant number of straight-line tracks that would be considered as turning tracks.

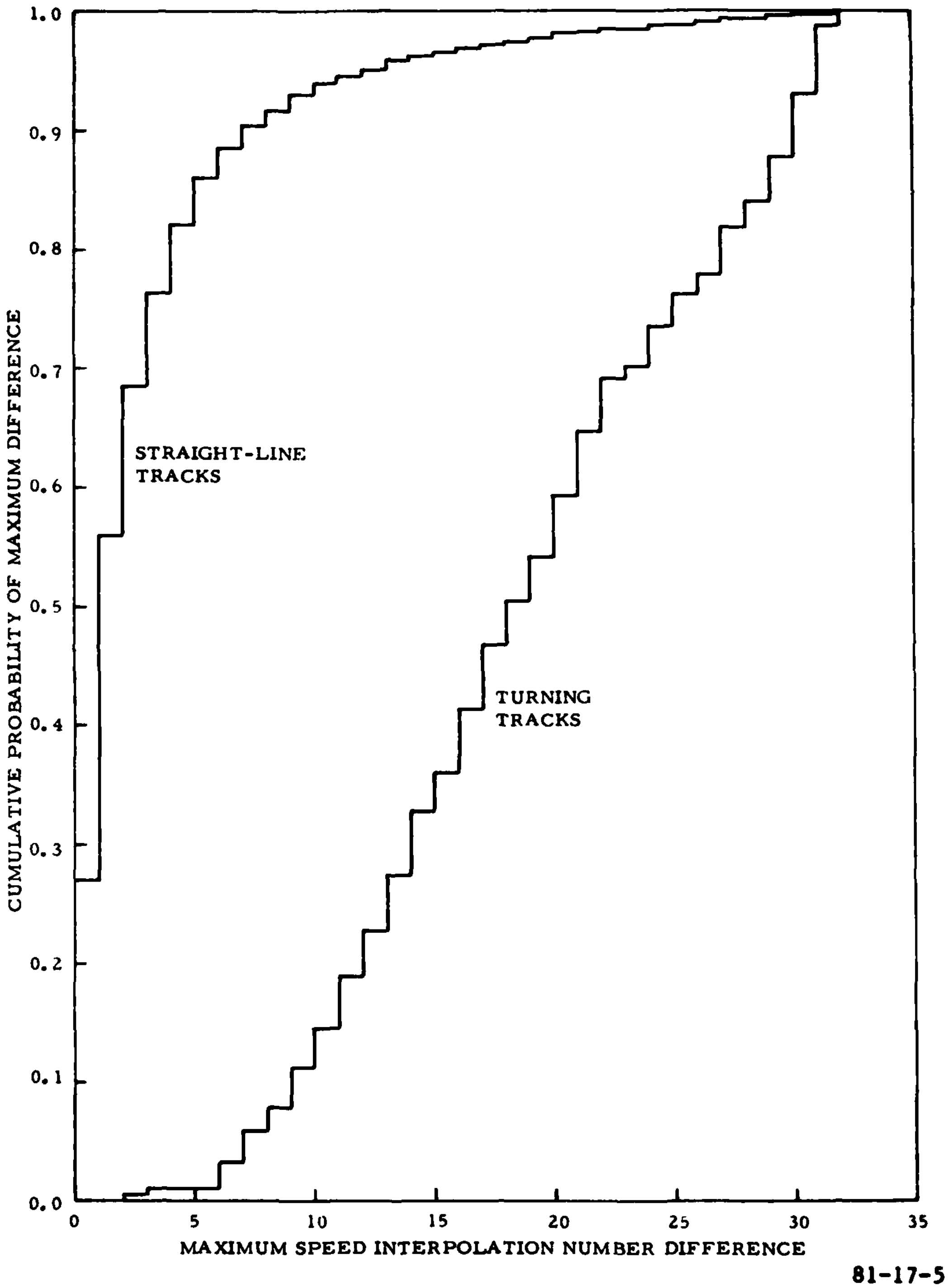


FIGURE 5. MAXIMUM SIN DIFFERENCES FOR DETERMINISTIC ANALYSIS

In order to improve the discrimination between straight-line and maneuvering targets, it is necessary to determine the circumstances under which straight-line tracks will give large maximum differences and eliminate these ambiguous cases from consideration. It is found, by examining the detailed results used to construct the cumulative distributions in figure 5, that the primary cause of large differences for straight-line tracks is the target crossing the first radial in a nearly perpendicular manner at a high velocity and at a location close to the radar.

For example, in the case where $\rho=10$, $\theta=90$, and V=450, the differences in the SIN for the two blind speeds (given in table 1 in section 3.1) were found to be 19 and 27, which are obviously high enough to be considered a turn. As the speed and distance to the sensor increases, the number of straight-line tracks that give large maximum differences decrease. By observing a large number of cases, it is concluded that if the cases where

$$\rho < a\,|V| \qquad (27)$$

with "a" being a small constant (0.12 knots $^{-1}$ is found to be satisfactory), are eliminated from consideration, most of the cases in which straight-line tracks have large maximum differences would also be eliminated. Naturally, some of the turning tracks would be eliminated from consideration as well, but, as the results presented in the following section show, this number would be relatively small and an insignificant price to pay for the improved discrimination obtained by using this criterion.

2.4 SIMULATION RESULTS CONCERNING SPEED INTERPOLATION NUMBERS.

The results obtained in the previous section deal solely with a deterministic analysis based on simple geometrical principles and ideal computations. In reality, however, the SIN are corrupted by noise, and the MTD data are not always received. As a result, in order to complete the study of the characteristics of MTD data, it is necessary to develop a stochastic simulation model to generate data of an appropriate statistical nature defined by the best available information. The simulation model can then be used to examine the MTD performance in a more realistic environment. Variations of the appropriate performance parameters are considered in order to cover the extremes likely to be encountered in practice and to evaluate the sensitivity of the results to variations in the operational characteristics of the data.

In order to simulate the operation of the MTD in a more realistic sense, random Gaussian noise is added to each SIN to simulate measurement and computational errors (with the resulting noisy SIN restricted to the range 0 to 63). In addition, the simulation includes cases in which one or more of the SIN were missing, which corresponds to situations in which the received signals are too weak to be detected. For such situations, the SIN difference is set equal to zero so that these cases simulate those in which no turn detection was found. From experimental data it is found that reasonable estimates for the blip/scan ratios are 76.1 percent for obtaining a SIN on both blind speeds, while in 5.4 percent of the cases neither of the SIN were received (private communication, J. Shannon, ARD-110; a more recent assessment is given in reference 28).

While the loss of SIN data causes a reduction in tracking performance (assuming it is used as intended), it does not prevent a target from being tracked. The position reports are based on the beacon system, so that the loss of SIN data for a given target is of little consequence compared to the loss of target position information. For cases in which the SIN data are not available, the tracking algorithm simply reverts to the standard bimodal version in which the smoothing constants are determined by the search area in which the position report is located.

The results presented in the previous section (figure 5) are based simply on an enumeration of the times a particular result is obtained, without any consideration given to whether or not the conditions would actually be found in practice. In order to develop a probabilistic model that corresponds to what would be found in reality, each of the parameters used to describe the geometry of figure 4 is assigned a probability distribution. An appropriate weighting factor can then be assigned to each simulation outcome (the maximum value of the differences in SIN on two successive scans). For simplicity, it is assumed that there are no preferred speeds and no preferred headings: speed and heading can be assumed to be uniformly distributed within the bounds specified previously (i.e., each value is assigned the same probability).

In determining range figures it is assumed that targets are uniformly distributed throughout the coverage area of the sensor so that the probability of a particular range being observed is taken as the ratio of the area of the ring containing the specified range to the total area of coverage. Since the MTD data would most likely only be used with data from preferred sites, the range limits are set at 5 nmi and 105 nmi. Assuming range is sampled every 10 nmi, as done previously, the results at 100 nmi are weighted according to the ratio of the area in the ring from 95 to 105 nmi to the total coverage area (5 to 105 nmi). As a result of the difficulty in distinguishing between straight-line and maneuvering targets at close ranges, it may be advisable to simply eliminate any data below a certain range threshold, knowing that such data would probably not in any case be used by the tracking algorithm.

The probabilistic specification given above for the parameters describing the simulation program allows the development of a histogram of the maximum differences that is weighted in a realistic manner. Naturally, the validity of results obtained this way can always be questioned, but the basic objective at this point is simply to extend the deterministic results, obtained previously, in some realistic manner. This is in order to determine performance parameters that would be found if the parameters of the physical situation did follow the postulated distributions.

As a result, it is now possible to quantify, as a function of threshold, the probability of false alarms in declaring straight-line tracks to be maneuvers and the probability of detection for maneuvering targets. Naturally, such an evaluation can form the basis for determining whether or not the MTD data can be used to detect maneuvers and, thus, the ability to influence the performance of the tracking algorithm for maneuvering targets.

The results of the simulations performed under the conditions described above are given in figure 6. At each possible combination of range, heading, and speed, the scan-to-scan maximum differences are computed in 100 stochastically independent experiments, each of which is weighted inversely in proportion to the sample size (100) and then weighted again in the manner described previously for range, heading, and speed. The figure 6 notation (σ=5.0, σ=2.0) refers to the standard deviations of the Gaussian random number generator. Because of quantization, however, the standard deviations of the errors in the SIN are actually 1.6 and 4.7, respectively, results that can be obtained using a technique developed elsewhere (reference 22).

The region denoted as the sensitive region corresponds to those cases for which $\rho < a\,|V|$, where a=0.12. As the results show, the size of this region (~15.5 percent) is sufficiently small that the feasibility of using the MTD data would not be jeopardized by simply eliminating those cases in which the results fell in this region. It might also be possible to calculate a different threshold for this region by using the estimated velocity calculated by the tracker in an attempt to salvage some of the data in the region, but as this would require significant computational resources to achieve very little in return, it is given no further consideration.

In examining the results in figure 6, it is seen that at a threshold in the range of 12 to 16, the number of false alarms on straight-line tracks (given by the difference between the probability of being at or above one unit below the threshold up to the sensitive region, as illustrated in figure 6) ranges from virtually none to a peak of about 10 percent, depending on the threshold and the standard deviation. It seems logical to conclude that since the region in which large differences are found was eliminated, the false alarm rate can be reduced to reasonable levels without unduly restricting application of the technique. The standard deviation and the range of thresholds chosen are intended to bound the results found in practice so that 10 percent should be an approximate upper limit on the false alarm rate, assuming postulated parameter distributions are correct.

The results for the maneuvering targets show that for threshold levels in the range of 12 to 16, the probability of detecting a maneuver (again given by the difference between the probability of being at or above one unit below the specified probability up to the sensitive region, as illustrated in figure 6) is between 48 and 62 percent. This range is primarily dependent on the threshold level rather than the noise level. For practical purposes, the results indicate that for a range of thresholds chosen for feasibility as a compromise between a reasonably high probability of detection and a sufficiently low false alarm rate, perhaps half of the turning targets can be detected in one scan.

Generally, in tracking, a false indication of a maneuver (and the consequent change of smoothing parameters) causes an undesirable perturbation of a straight-line track. For practical purposes, a one-scan delay in the switching of the smoothing parameters should be used so that no action can be taken until two consecutive maneuver indications are observed.

The introduction of a one-scan delay before switching the smoothing constants is not a significant penalty to pay in order to achieve more reliable results, since the change in tracking performance due to the use of the large search area smoothing constants one scan earlier is not significant in a practical sense. Other studies have also found the one-scan delay to be a useful technique (references 12 and 19 through 21), although in some cases the first large search area return was simply discarded.

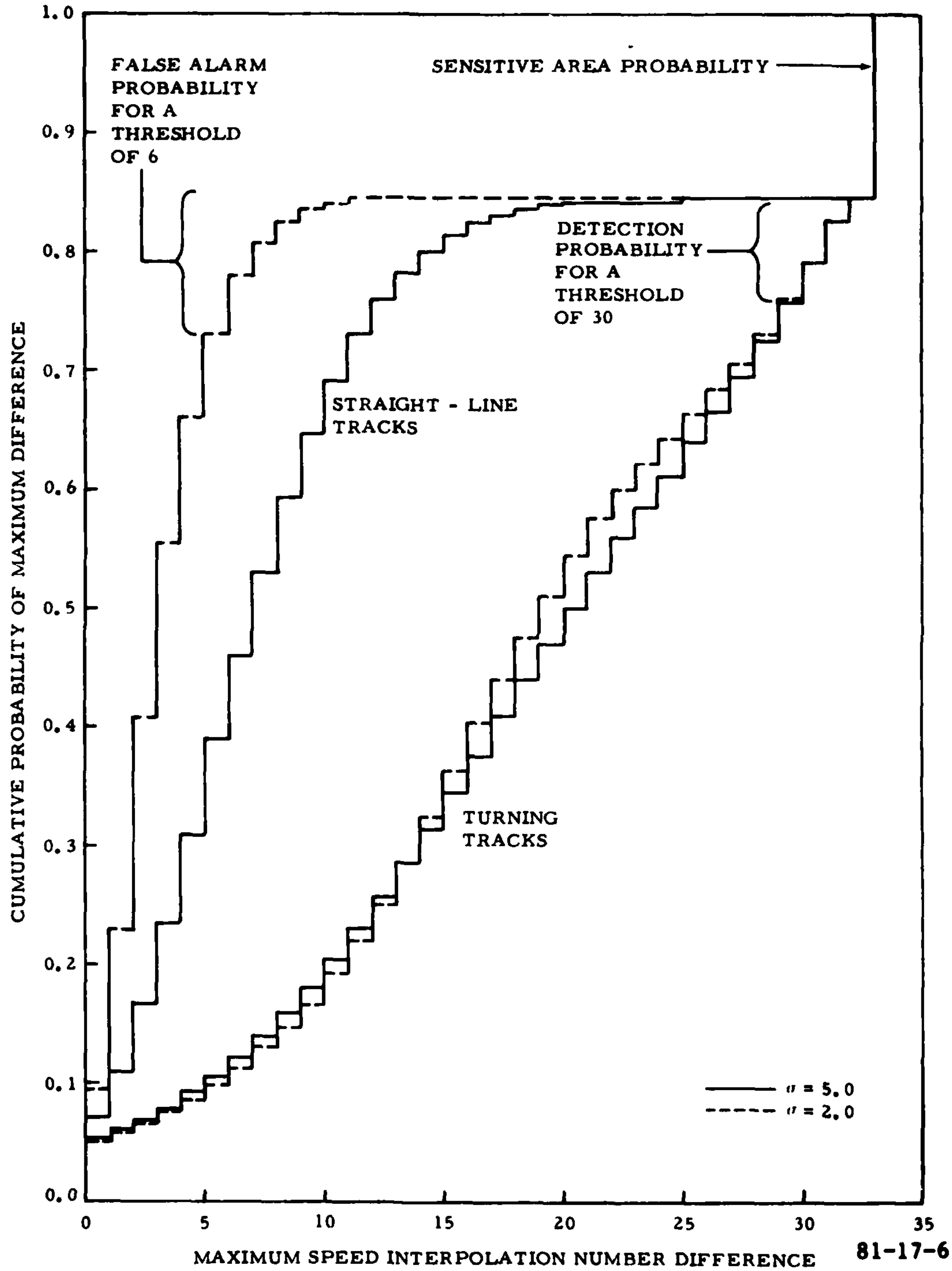


FIGURE 6. MAXIMUM SIN DIFFERENCES FOR STOCHASTIC CASE

2.5 CONFLICT ALERT SIMULATION.

Since the basic objective in the present study is to examine the impact of the use of the data from the MTD on the performance of the Conflict Alert algorithm (reference 3), a brief description of this algorithm is given below. As was the case with the tracking algorithm, the simulation procedure used for the Conflict Alert algorithm is considerably simplified, compared to the actual operational program. Because of these deviations, a description, is warranted.

The major differences from the operational program are in the following four areas: (1) altitude processing is not considered at all, (2) subcycles are eliminated along with the associated track-sorting function, (3) the entire simulation uses floating-point arithmetic, as opposed to the fixed-point arithmetic used in the operational program, and (4) the sensor, tracking algorithm, and Conflict Alert algorithm operate in perfect synchronism at the same rate determined by the rotation period of the sensor.

The simplified Conflict Alert algorithm consists of a coarse lateral filter and a fine lateral filter. For simplicity, the terminology and notation follow those used in the functional specification for the operational program (reference 3). The coarse lateral filter is used to select track pairs for further evaluation by Conflict Alert. Given the position coordinates of the ith and jth track, (X_i, Y_i), and (X_j, Y_j) respectively, this track pair passes the coarse filter test if (parameters specified by acronyms will be defined later)

$$(X_i - X_j)^2 + (Y_i - Y_j)^2 < MAXR^2 \qquad (28)$$

and track pairs passing this filter are subjected to the fine lateral filter. Track pairs not passing this filter are rejected from all further tests. The fine lateral filter is composed of two separate tests: a test for current lateral conflict, and one for predicted lateral conflict. A pair of tracks is in current lateral conflict if the current separation between tracks violates safe limits. Let

$$R_o^2 = (X_i - X_j)^2 + (Y_i - Y_j)^2 \qquad (29)$$

then, if $R_o^2 \leq SEPR^2$, a current lateral conflict exists.

A predicted lateral conflict is based on an estimation of the future position. Since the velocities used in this process are derived from measurements subject to random errors, the prediction of a future conflict must be defined very carefully. As a result, a pair of tracks is in predicted lateral conflict only if it meets all the following conditions:

a. The tracks are generally converging toward each other. Let

$$V_c = (X_i - X_j)(\dot{X}_i - \dot{X}_j) + (Y_i - Y_j)(\dot{Y}_i - \dot{Y}_j). \qquad (30)$$

then the inequality, V_c < VELC, must then be satisfied.

b. The tracks are not closing excessively slowly. Let

$$V^2 = (\dot{X}_i - \dot{X}_j)^2 + (\dot{Y}_i - \dot{Y}_j)^2, \tag{31}$$

then the inequality $V^2 > CLOS^2$ must then be satisfied.

c. The predicted minimum separation between tracks violates safe limits. Let the time to minimum separation, T_m, be $T_m = -V_c/V^2$. If $V^2 = 0$, then $T_m = 0$. The predicted minimum separation squared, $R_m{}^2$, is given by $R_m{}^2 = R_o{}^2 + V_c\ T_m$. Then the inequality $R_m{}^2 \leq SEPM^2$ must be satisfied.

d. The lateral safe separation limit is violated within the warning time, WRNT. This requirement is satisfied if the time to minimum separation, T_m, is less than or equal to WRNT, or if the predicted separation squared at WRNT, $R_p{}^2$ (WRNT) $= R_o{}^2 + 2V_c$ WRNT $+ V^2$ WRNT^2, violates safe separation limits ($R_p{}^2$ (WRNT) $\leq$ SEPP^2).

Once the above tests are completed, and it is determined that this particular pair has been in a condition of conflict, either current or predicted, at least twice in the past three successive tracking cycles, an aircraft pair is eligible for controller alert generation.

The parameters that are used in the conflict determination process are selected from two alternate sets of parameters. The determination of the set of parameters to use is based on various criteria (see reference 3, section 14.2), but for the purposes of this study, the "A" set of parameters in table 1 is used unless the track pair under consideration is detected to be in a condition of conflict within the last two tracking cycles. In this case the "B" set is used. The parameter values in table 1 correspond to those currently in use operationally (reference 23), but note that MAXR, VELC and CLOS are common to both parameter sets.

TABLE 1. PARAMETER VALUES FOR CONFLICT ALERT ALGORITHM

Parameter	Parameter Set A	Parameter Set B	Units
WRNT	2.5	2.0	min
SEPR	5.0	4.2	nmi
SEPM	6.0	4.8	nmi
SEPP	6.0	4.8	nmi
MAXR	55		nmi
VELC	8		nmi^2/hr
CLOS	0.7		nmi/min

The algorithm specified in table 1 duplicates the planar operation of the Conflict Alert function in all important aspects with one notable exception. Since the Conflict Alert algorithm is intended to detect hazardous conditions one obvious measure of success is the warning time to a critical situation. Naturally, it is desired that sufficient warning time be available to allow for controller intervention in situations in which this is warranted. For this reason, the warning time to critical situations is evaluated in various scenarios discussed later. The particular aspect of the operational program that differs from the simplified algorithm is the fact that the computational resources required for the Conflict Alert function dictate that only one-third of the coverage area of the Air Route Traffic Control Center be processed during each tracking subcycle (with two tracking subcycles per tracking cycle).

As a result, the warning times given in this report can be considered to be the equivalent of one tracking cycle larger than a worst case field condition in which the alert condition occurs in the last area of the coverage region processed. For the purposes of this study it is assumed that there is no difference between the tracking cycle and the rotation period of the sensor, although in the typical operational environment a tracking cycle is approximately 12 seconds, while the rotation period of a typical radar is approximately 10 seconds.

The warning time to a critical situation is only one measure of the performance of a Conflict Alert algorithm. Warning time is a measure of the positive aspect of the protection provided by this function. Another performance factor of interest is a negative aspect, which occurs when alert conditions are indicated in situations in which no hazard truly exists. The most obvious example of such a situation is the case of two aircraft flying on intersecting trajectories, but one turning before a separation violation occurs. In this case, a tracking algorithm that is unresponsive, (i.e., allows the development of large bias errors) may indicate a hazardous situation exists, while a more responsive tracking algorithm (one tracking at a reduced level of bias error) may not.

For this negative aspect of algorithm performance, an alternative measure is developed in the form of a "nuisance alert area." This statistic provides a measurement of the size of the area in which invalid alerts are generated because maneuvering targets have avoided separation violations. Therefore, the nuisance alert area is a measure of the false alarms declared by the Conflict Alert algorithm and is generally proportional to the bias observed in maneuvering situations. A more precise definition of the nuisance alert area is provided in the following section.

3. SIMULATION RESULTS.

3.1 DESCRIPTION OF TRACKING SIMULATION PROCESS.

The basic description of the tracking algorithm was given in section 2.2, but in order to simulate the operation of the Conflict Alert algorithm, described in section 2.5, it is necessary to simulate pairs of tracks simultaneously, and then process them by the Conflict Alert algorithm. As a result, in each simulation there are two true tracks for which random radar returns of the proper statistical characteristics are generated, the number of track pairs constituting the size of

the random sample. Each random track is statistically independent of all other random tracks. Since the asynchronous operation of the sensor and tracking algorithm is not being considered, the radar is assumed to simultaneously interrogate each target at a fixed rate.

The simulation parameters defining the standard scenario conditions are given in table 2, except for the parameter values used in the Conflict Alert algorithm, which were given in table 1. The starting point for the tracks are chosen so that the important aspects of the scenario take place sufficiently far from the radar that the MTD data will be used; that is, the simulation is outside the area defined by (27). Any deviation from these standard parameter values is noted in the text. The computations for the tracking and Conflict Alert algorithms are all performed using floating-point arithmetic to eliminate the computational errors associated with the fixed-point arithmetic used for field implementation.

The errors in the SIN generated by the MTD are generated by a floating-point Gaussian random number generator and then quantized to integer values. The standard deviation of 2.37 used in the floating-point random number generator is necessary to give a standard deviation of 2 in the quantized results. It has already been determined how the quantization process in the floating point to integer conversion results in a reduction of the variance (reference 22).

The standard deviation and blip/scan ratio used for the MTD are slightly different from those used in section 2.3 and represent a more recent assessment of what would constitute an optimistic performance level for the MTD (private communication, J. Shannon, ARD-110; see also, reference 28). The justification for this choice of values is simply that if the simulation results are encouraging, and if field experiments with the MTD indicated different performance values, further experimentation with less optimistic values would be justified. The threshold used for maneuver detection with the MTD is set at 7, which is slightly more than three times the standard deviation of the errors. A maneuver is detected when the scan-to-scan change in the maximum difference in the SIN (for the two blind speeds) is equal to or greater than the maneuver detection threshold.

The standard smoothing parameters given in table 1 correspond to those currently in operational use (reference 23) while the track-oriented smoothing parameters are based on the results of a preliminary study (reference 5) in which various alternative sets of smoothing parameters were examined. As a result of the computational requirements for performing the simulation, only one set of track-oriented smoothing parameters is chosen for evaluation. Since the objective in the use of track-oriented smoothing is to reduce the heading error, the chosen parameter values provide a fairly large weighting factor for velocity. The result is that the peak heading error in a turn is reduced by approximately a factor of two.

While it is possible to obtain even greater reductions in the peak heading error by using larger smoothing parameters, it is found that larger smoothing parameters result in considerable overshoot at the end of a turn, thus giving an oscillatory response. Because it is not the intent of the present study to optimize the tracking parameters, the choice of parameters is made in such a manner that if an improvement in performance is to be found, it is expected that such an improvement would be seen under the conditions used for experimentation. One final point which should be noted is that the turn rate used for maneuvering targets is the standard turn rate, as used for simulation (reference 24), and which assumes a 30° bank angle.

TABLE 2. NOMINAL SIMULATION PARAMETERS

Population sample size, N:	250
Total simulation duration, N_s:	50 or 100 scans
Scan time, T:	10 seconds
Blip/scan ratio:	0.95
Radar range standard deviation, σ_ρ	0.125 nmi
Radar azimuth standard deviation, σ_θ	3 ACP (4096 ACP/2π radians)
Dynamic search area design probability:	0.95
A_S, small search area	
Shape:	circular
Radius, dynamic search area	$r_S = \max(0.3, 0.01\rho)$ ρ = target range
Radius, fixed search area	$r_S = 1.0$ nmi
A_L, large search area	
Shape:	circular
Radius, dynamic search area	$r_L = r_S + 4VT$ $V = \sqrt{V_x^2 + V_y^2}$
Radius, fixed search area	$r_L = 4.0$ nmi
Smoothing parameters for:	
Small search area	$\alpha_S = 0.3125$ $\beta_S = 0.046875$
Large search area (standard)	$\alpha_L = 1.0$ $\beta_L = 0.15625$
Large search area (Track-Oriented Smoothing)	$b_1 = 0.5$ $b_2 = 1.0$ $\beta_1 = 0.42$ $\beta_2 = 0.84$
Moving Target Detector	
Standard Deviation before quantization after quantization	$\sigma = 2.37$ $\sigma = 2.00$
Blip/scan ratio	
Both SIN	0.92
One SIN	0.05
Neither	0.03
Maneuver Detection Threshold	7
Blind speeds	78.23 knots 94.54 knots

3.2 SIMULATION RESULTS FOR WARNING TIME STUDIES.

The maneuver detection options selected for use in this study were given in section 2.2.4. The basic objective in the maneuver detection process is to use larger smoothing constants in the maneuvering case, in order to reduce the transient bias error, and smaller smoothing constants for straight-line trajectories to give a satisfactory level of noise rejection. The smoothing constants used for a maneuver are given in table 2 under the large search area for both the current operational parameters and the track-oriented smoothing parameters. The five maneuver detection options are denoted as follows:.

F(N) - Fixed search area with no delay in the use of the large search area smoothing constants.

D(N) - Dynamic search area with no delay.

D(D) - Dynamic search area with a one scan delay in the use of the large search area smoothing constants.

M(D)/D(D) - MTD data is used for maneuver detection with a one-scan delay and combined with the dynamic search area, also with a one-scan delay.

M(N)/D(D) - MTD data is used with no delay and combined with the dynamic search area with a one-scan delay.

The fixed search area with no delay corresponds to the maneuver detection feature currently specified in the operational program. Whenever a one-scan delay is specified, this means that the first return exceeding the maneuver threshold is smoothed using the small search area smoothing constants. The large search area smoothing constants are only used for subsequent returns exceeding the maneuver thresholds. The only exception to this rule is in the M(D)/D(D) case in which the large search area smoothing constants are used immediately if both the MTD data and the dynamic search area indicate a maneuver has been detected.

The scenarios used for the warning time tests are illustrated in figure 7. The scenarios were selected to be representative, but obviously not exhaustive, of the situations in which conflicts might be observed in operational situations. The target velocities used in the simulations are 220 and 480 knots in all cases, except the in-trail overtakes in which target velocities of 480 and 420 knots are used. With the exception in the case of the in-trail overtakes, simulations are run for both the case of a critical situation, in which the targets are actually at the same position at the same time, and for that in which a critical situation does not develop, although the minimum separation distance violates the separation standards. In the case of the last scenario, simulations were run for separations of 6 and 12 nmi.

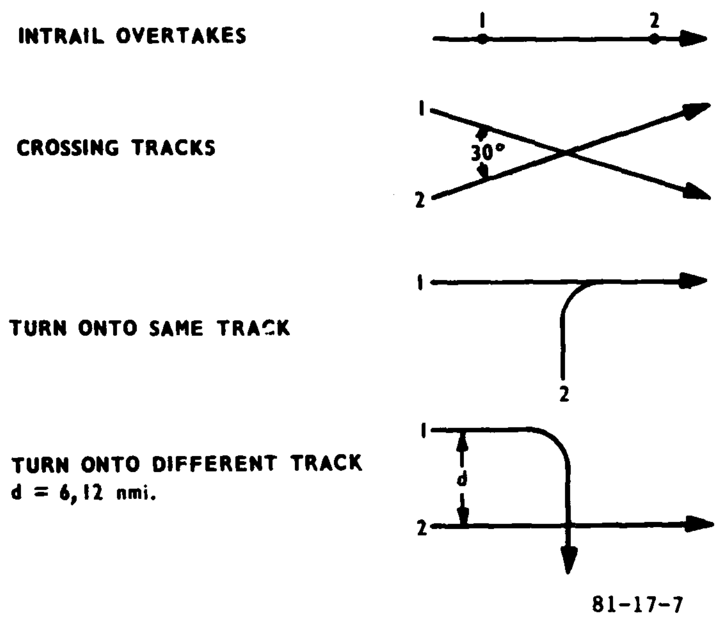


FIGURE 7. ILLUSTRATION OF SCENARIOS FOR WARNING TIME TESTS

3.2.1 Simulation Results For Warning Times In Critical Situations.

The simulation results for the mean warning time to critical situations are given in table 3. In all cases, the reference time used as the time origin is the time of zero separation between the two true tracks. In reviewing the results, it is seen that in most cases there is very little difference in the simulation performance regardless of the smoothing parameters or the type of maneuver detector used. An obvious reason for this is the fact that the exact same sequence of random numbers is used in each simulation, resulting in deterministic rather than random differences. In addition, time is always measured in 10-second increments corresponding to the basic cycle time of the simulation.

When the results are examined in a slightly different manner than the mean warning time, it is found that the time (or, equivalently, the scan) at which the 50th and 80th percentile of the number of tracks in an alert status is reached shows in almost all cases no more than a one-scan difference in the results. A typical value of the standard deviation in the warning time, averaged over the maneuver detection option results, is given for each scenario to illustrate the level of variation within each simulation for each parameter set. The variation in performance increases significantly with the use of the track-oriented smoothing parameters, which would be expected since the larger smoothing parameters result in a significantly higher level of noise.

TABLE 3. SIMULATION RESULTS FOR MEAN WARNING TIME TO CRITICAL SITUATION (IN SECONDS)

Smoothing Parameters:	Standard						Track-Oriented					
Maneuver Detector:	F(N)	D(N)	D(D)	M(D)/D(D)	M(N)/D(D)	$\sim\sigma$	F(N)	D(N)	D(D)	M(D)/D(D)	M(N)/D(D)	$\sim\sigma$
Scenario												
Straight-Line												
In-Trail Overtake	414.0	417.5	405.1	407.5	414.0	38	404.5	409.9	403.2	397.5	405.7	51
30° Crossing												
220 knots	261.6	261.8	261.7	261.8	262.4	9	261.3	264.6	262.2	259.2	264.8	18
480 knots	180.0	179.4	180.6	178.4	178.7	15	183.6	185.1	180.7	182.5	190.7	30
Maneuvering												
Turn, Same Track												
220 knots	182.6	181.4	182.4	182.3	181.8	13	182.2	179.1	182.8	182.4	181.5	17
480 knots	169.2	169.1	169.2	169.2	169.0	11	166.9	165.4	168.7	166.6	166.3	17
Turn, Diff. Track 6 nmi Separation												
220 knots	65.4	68.0	64.0	68.5	68.2	7	66.4	82.8	66.1	76.8	79.3	15
480 knots	28.4	30.2	22.2	30.7	31.0	7	34.0	49.9	25.2	*	*	28
12 nmi Separation												
220 knots	114.4	116.1	114.6	115.2	115.3	11	142.6	141.9	141.4	142.0	141.1	19
480 knots	45.3	45.5	45.1	45.8	45.8	6	50.4	55.0	47.7	57.4	58.2	11

*Results invalid: see text.

The significance of the performance differences that are observed must be examined in light of the differences between the simulation model and the operational environment. It has already been noted in sections 2.1 and 2.2, that certain aspects of the operational program, predominantly operation in a multisensor environment, are not modeled very closely. As a result, it is considered that any difference on the order of one scan (10 sec.) in the simulation results is of no practical significance, since the simulation algorithm is not considered to be a model sufficiently accurate to reflect operational differences of this magnitude. In view of this, there are only a few cases in table 3 in which the performance differences might be considered significant, and all of these involve the scenario of a turn onto a different track. In the case of 6-nmi separation, the results do not show a consistent level of improvement, while the results for a 12-nmi separation are very consistent.

In examining in more detail the simulation results for the scenario of a turn onto a different track with a 6-nmi separation, it was observed that a significant number of alerts (in one case, 16 percent) are actually declared while the targets are still on the straight-line portion of the trajectory. These alerts then, are actually false alerts. No improvement in warning time is actually obtained in this case, and so the numerical data are not presented.

In fact, the performance with track-oriented smoothing actually deteriorates in the sense that relatively few alerts are generated in the same case using the standard tracking parameters. The results in this case illustrate the fact that the speed and heading errors increase significantly for straight-line tracks using track-oriented smoothing, as would be expected from the significantly larger β value. This result is also in line with that obtained in a previous study which showed significant degradation of the straight-line tracking performance due to the erroneous use of the large search area smoothing parameters (reference 18).

Thus, the only situation in which even a marginal improvement in warning time is noted is in the case of the turn onto a different track with a 220-knot velocity and an initial track separation of 12 nmi. Even in this situation, however, the improvement in warning time of the performance of track-oriented smoothing over that of the conventional smoothing parameters is only 1 to 2 scans.

A fact that should be obvious, but is worth noting, is that the use of a 2-minute position prediction does not necessarily result in a 2-minute warning. The results in table 3 show warning times from less than one-half minute to over 6 minutes. The reason for this variation is readily apparent when the scenario in question is examined. In the case of the in-trail overtake the relative closing speed is 60 knots and, if an alert condition is initially specified by a 6-nmi separation in the predicted position, then the warning time should be — and is — on the order of 6 minutes.

In the case of the 480-knot turn onto a different track with closely spaced parallel trajectories, the two targets are in a current violation status almost from the start of the turn. Since the targets are closing at a worst-case velocity of 8 nmi/min and the tracks are separated by only 6 nmi, the reason for the 30-second warning time is readily apparent, especially considering the two-out-of-three cycle display logic in the Conflict Alert algorithm. Hence, the results that are obtained seem reasonable, but confirm the fact that a 2-minute prediction does not necessarily result in a 2-minute warning.

3.2.2 Simulation Results For Noncolliding Trajectories.

Another case of interest is the less hazardous situation in which two targets converge and violate the separation standards, but because the minimum separation is not zero, a collision does not occur. The results for these experiments are given in table 4. In the cases in which two different sets of results are given for each scenario, the scenario is repeated twice so that results can be obtained depending on whichever target reaches the point of intersection of the trajectories first. The crossing track scenarios are not run in pairs, as just described, because one case is simply a symmetrical version of another.

In all cases, the time origin is taken as the time of closest approach, and the warning time cannot be compared directly to those given previously because the interpretation of the significance of these results is open to question. One could also choose the exact time of separation violation as a time origin. Although some of the results in table 4 indicate very short warning times, these results do not refer to the time to collision and so do not represent the same degree of danger as the situations for the results in table 3.

The results obtained in the noncollision scenarios are very similar to those obtained previously; namely, in most cases there are no significant differences in performance between the various maneuver detection options for either the track-oriented smoothing parameters or the conventional smoothing parameters. Again the apparent performance improvement for the case of a turn onto a different track with a 6-nmi separation is due to an increase in the number of alerts declared on the parallel track position of the scenario. This corresponds to a degradation in performance because the alerts are erroneous. Likewise, the results for a 220-knot target and a 12-nmi separation can be reliably expected to result in an operational improvement of only 1 to 2 scans. Such minor improvements obtained under such limited conditions indicate that the few improvements are of little practical significance and do not on their own merit constitute sufficient justification for changing either the smoothing parameters or the maneuver detection process.

3.3 SIMULATION RESULTS FOR ANALYSIS OF NUISANCE ALERT AREAS.

3.3.1 Description of Nuisance Alert Area Concept.

The results presented in the previous section provide an indication of the positive aspect of the performance of the Conflict Alert algorithm; that is, a measure of the warning time to a critical situation. In this section, an alternative performance measure is discussed that is a measure of the negative aspect of algorithm performance — the generation of false alerts. The situations that are considered in this analysis are illustrated in figure 8. These scenarios constitute cases in which two targets are on converging trajectories but one target turns before a critical situation develops. Although many other scenarios could be constructed in which alerts are erroneously generated, the three given here are sufficient for evaluating the concept under consideration.

TABLE 4. SIMULATION RESULTS FOR MEAN WARNING TIME FOR SEPARATION VIOLATION (IN SECONDS)

Smoothing Parameters:		Standard						Track-Oriented					
Maneuver Detector:		F(N)	D(N)	D(D)	M(D)/D(D)	M(N)/D(D)		F(N)	D(N)	D(D)	M(D)/D(D)	M(N)/D(D)	
Scenario	Min. Sep.(nmi)						$\sim\sigma$						$\sim\sigma$
						Straight-Line							
30° Crossing													
220 knots	3.9	198.9	209.1	198.6	198.7	199.0	27	202.9	239.0	203.4	205.8	217.3	43
480 knots	3.9	145.8	147.7	146.0	150.8	152.4	18	152.3	169.7	147.4	172.5	181.3	34
						Maneuvering							
Turn, Same Track													
220 knots	3.0	154.2	154.1	154.7	154.2	154.0	12	154.6	153.3	154.3	153.4	153.6	18
	2.5	159.3	158.7	159.5	159.3	158.4	11	158.7	152.6	157.7	156.8	156.0	16
480 knots	3.0	149.8	149.6	149.9	149.9	149.9	11	146.6	147.0	149.3	146.5	146.5	15
	3.0	143.0	142.0	143.8	142.0	139.7	12	140.7	138.4	142.2	134.6	134.8	22
Turn, Diff. Track													
6 nmi Sep.													
220 knots	3.6	16.7	21.8	15.2	21.6	21.6	6	16.9	40.9	17.9	*	*	18
	3.6	76.9	80.4	77.2	77.9	77.6	11	77.0	91.9	84.5	89.4	90.4	18
480 knots	3.9	10.6	12.1	10.2	12.7	13.3	4	13.4	26.6	4.5	*	*	25
	4.0	14.3	15.8	14.4	15.5	15.4	7	14.7	21.0	7.6	23.3	28.2	23
12 nmi Sep.													
220 knots	3.6	77.9	80.0	77.6	77.7	77.8	9	102.1	100.5	97.4	103.0	102.0	16
	3.6	115.7	118.2	114.8	113.4	113.9	14	155.1	154.9	152.0	148.9	147.9	30
480 knots	3.5	34.3	36.4	37.2	37.1	36.9	5	46.7	48.0	42.0	48.8	49.0	8
	3.9	28.3	29.2	27.6	28.7	28.4	10	33.8	37.3	31.7	39.4	41.0	14

*Results invalid: see text.

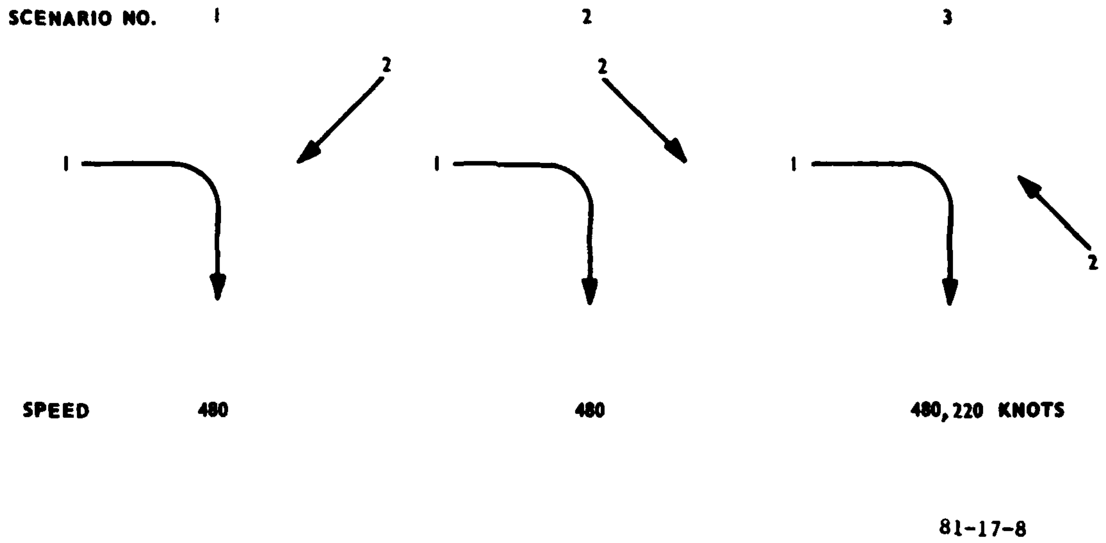


FIGURE 8. ILLUSTRATION OF SCENARIOS USED FOR NUISANCE ALERT AREA ANALYSIS

The design of an algorithm for prediction of separation violations or critical situations requires an implicit balance between sensitivity and an excessive alarm rate. An algorithm that has very stringent requirements for the generation of an alert condition will obviously be less likely to create an erroneous alarm than one that generates alarms under very loose requirements. The objective in designing the algorithm should be to choose parameter values that minimize false alarms yet provide sufficient warning time in situations in which an alert is warranted. Naturally, the tracking algorithm performance will affect the parameters chosen for use in the alert generation algorithm.

Since the Conflict Alert algorithm must make use of the position and velocity data that is computed by the tracking algorithm and often corrupted through measurement and computational errors, the Conflict Alert algorithm output is not perfect. As a measure of the propensity of the Conflict Alert algorithm to generate unwanted or nuisance alerts, a performance measure is devised that is defined on the simulation output and quantifies this negative aspect of system performance. An unwanted or nuisance alert is an alert that would not have been generated in the absence of measurement errors and with perfect knowledge of the present position and velocity of the target. The generation of nuisance alerts thus depends on two factors: (1) the inherent measurement errors in the radar data supplied to the tracking algorithm, and (2) the development of a bias in both position and velocity for maneuvering targets.

The illustration given in figure 9 helps to explain the concept of a nuisance alert area. Suppose for simplicity, that a conflict is defined simply as the condition in which the linear projections of the velocity vectors of two tracks are within a distance, r_m of one another. If the velocity projections from the current positions are separated by more than r_m then no alert condition exists. In fact, the conflict generation criteria actually used, given in section 2.5, are more complex, but for tutorial purposes these complexities are extraneous and will be ignored. The third scenario in figure 9 was chosen for illustration, but the same explanation holds for all scenarios.

The vectors in figure 9 illustrate linear velocity projections based on the true velocity (for equal time intervals) of a maneuvering target and for a family of straight-line trajectories that might intersect the maneuvering target. The number of intersecting straight-line trajectories that can be defined is infinite and the ones given are only for illustration. Consider the case at scan 1, just before the start of the turn, in which two examples are given for projections of straight-line trajectories. Any target on either of these two trajectories that is behind (to the right) of the scalloped line denoted as the boundary of the false alarm area (i.e., on the trajectories defined by the dashed lines, which are included for illustration only) should not generate an alert, since the velocity projections are based on the knowledge of the true position and velocity.

In the case at scan 2, there are three velocity projections to illustrate the straight-line trajectories. Again, any target with a true position behind in time with respect to the boundary of the false alert area should not generate an alert, given perfect position and velocity information. Note that "perfect information" means knowledge of the true position and velocity only up to the present — not the future trajectory of the target. At each scan, there will be, in fact, an infinite number of parallel straight-line trajectories positioned so that the alert generation criterion is just met; the velocity projections are separated by exactly r_m, and the locus of the true postion on these straight-line trajectories for which this is true define the boundary of the false or nuisance alert area. Note that the boundary of the nuisance alert area, as just defined, imposes a specified synchronization between the true positions of the two tracks under consideration (one maneuvering and the other straight-line).

Consider now a realistic, imperfect tracker in which a bias develops in the position and velocity as the target turns. In this case, some alerts are generated that would not have been called had the true positions and velocity of the target been known. This condition is illustrated in figure 9, by the point denoted as the smoothed position at scan 3 showing the effect of the lagging position and velocity, and at which the lag in heading is particularly significant. The reason for the generation of nuisance alerts should now be obvious from the position of the alert generation region for the imperfect tracker at scan 3.

Note that the tracks that were outside the alert generation region for the ideal tracker at scan 2 have now moved one scan ahead, as illustrated by the circle for the predicted position of one of the tracks. Two of these tracks will obviously be inside the alert generation region for the imperfect tracker at scan 3. A tracking algorithm that is more responsive (i.e., follows a turn more closely) could be expected to sweep past the straight-line tracks illustrated in figure 9 faster than an unresponsive tracker. Therefore, for such a scenario the responsive tracker should generate fewer alerts than the unresponsive tracker.

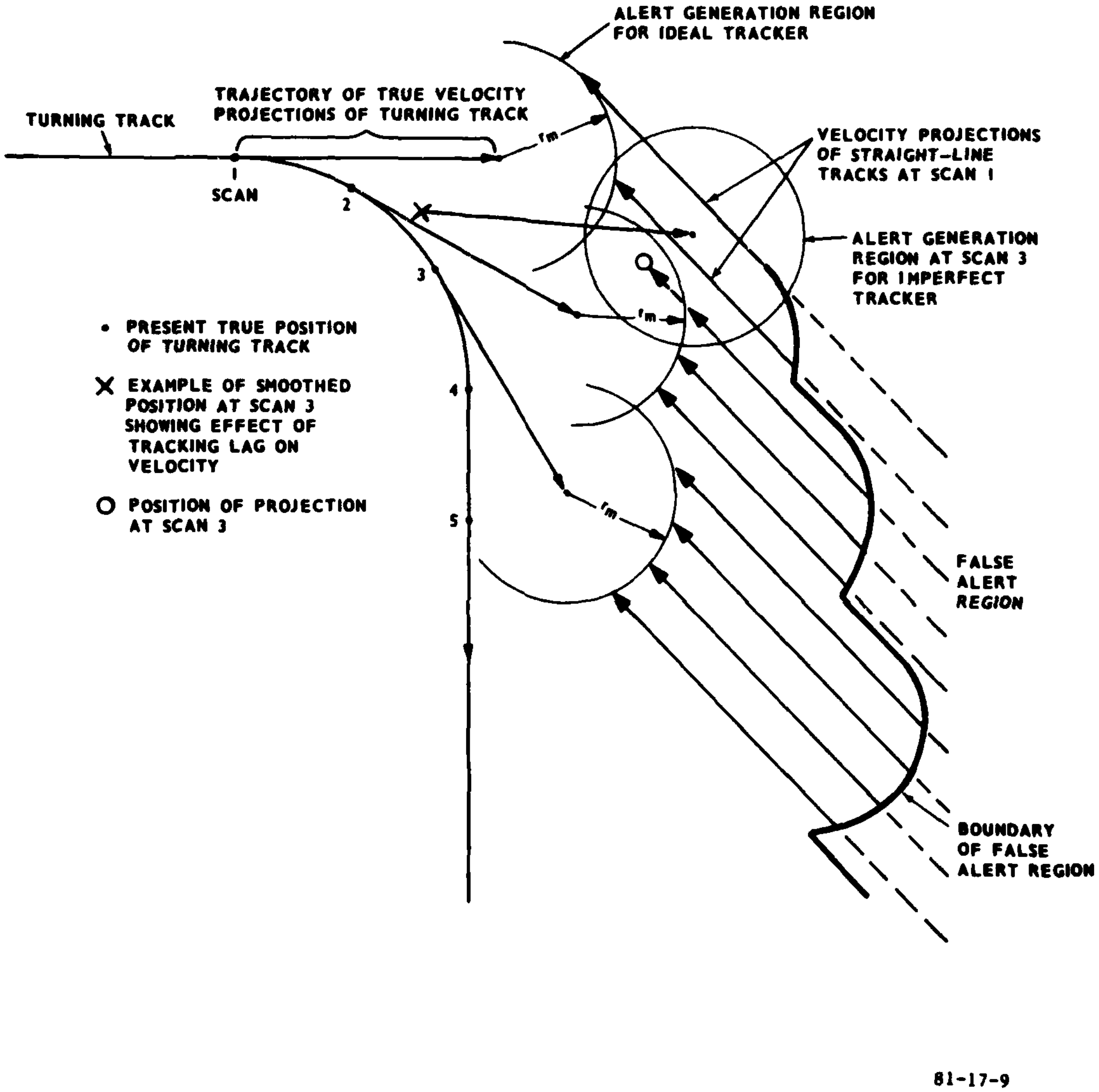


FIGURE 9. ILLUSTRATION OF NUISANCE ALERTS CAUSED BY HEADING LAG IN TRACKING (SCENARIO 3)

The discussion above explains the reason for the generation of nuisance alerts on a qualitative basis. In order to evaluate the efficacy of a particular tracking algorithm, or modification of an algorithm in reducing nuisance alerts, it is necessary to develop a quantitative measure of this aspect of system performance. The quantitative measure developed in this case is the nuisance alert area, which is simply the average size of the area in which nuisance alerts are generated for a particular algorithm in a specified scenario. Naturally, the tracking algorithm that gives the smaller nuisance alert area is the better algorithm by this criterion. The obvious expectation in this case is that the number of alerts in an operational environment will change in proportion to the change in the nuisance alert area.

The mathematical formulation of the nuisance alert area is based on the fact that for every pair of tracks consisting of the one maneuvering trajectory of interest and any one of the infinite number of straight-line tracks that can be defined, there is a semi-infinite time series corresponding to the probability of an alert as the scenario progresses. In order to combine these time series into a more compact form, only the maximum probability of an alert is considered.

For each pair of true trajectories there is only one number representing the performance of the tracking and Conflict Alert algorithms. If the maximum probability of an alert is averaged over the region in the vicinity of the maneuver, this provides a measurement of the size of the nuisance alert area which includes the density of alerts. Mathematically, the nuisance alert area measurement is defined on the Cartesian plane as

$$N_A = \iint_{(x,y)\epsilon A,} \max_t \, p(x,y,t) \; I(x,y) \; dA \qquad (32)$$

where A is the area surrounding the maneuver under consideration. I(x,y) is an indicator function defined as

$$I(x,y) = \begin{cases} 1, & \text{if projections of the true velocity are always separated by } r_m \text{ or more.} \\ 0 & \text{otherwise.} \end{cases}$$

In other words I(x,y) is a decision function which defines an alert as a true alert or a false alert (I(x,y) = 1 to the right of the boundary in figure 9), and p(x,y,t) is the probability of an alert as a function of time for a trajectory starting at the point (x,y). Naturally, the function p(x,y,t) is defined over the entire Cartesian plane, but only those points that are in the nuisance alert area need to be considered.

Since it is not possible to evaluate (32) analytically, a statistical simulation approach is taken. As in the case of the warning time analysis, the simulation is based on a sample of 250 pairs of tracks, and the potential region of the nuisance alert area is sampled at discrete points (x_i,y_i) with the value of $p(x_i,y_i,t)$ assumed to hold throughout some small differential area A_i. Hence, (32) is approximated by the sum

$$N_A = \sum_i \max_t \hat{p}(x_i,y_i,t)\ I(X_i,Y_i,)A_i \tag{33}$$

where $\hat{p}(x_i,y_i,t)$ are the sample functions defined on the simulation output that specify the relative number of track pairs for which an alert condition is detected. The alert condition in this case is defined by the actual operational *criterion given in section 2.5.* If all the points (x_i,y_i) are selected so as to be in the nuisance alert area, the indicator function in (33) can be ignored.

3.3.2 Nuisance Alert Area Results.

Since the approximation of the nuisance alert area is a function of the areas chosen for sampling and the starting points of the simulations, the explicit areas and starting points chosen for the evaluation of (33) are given in figures 10 to 12 for each of the scenarios under consideration.

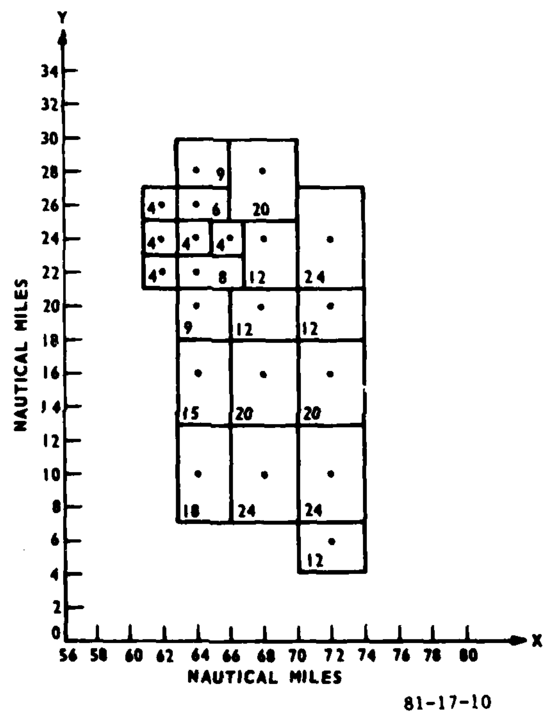


FIGURE 10. ILLUSTRATION OF AREA WEIGHTING FACTORS FOR SCENARIO 1

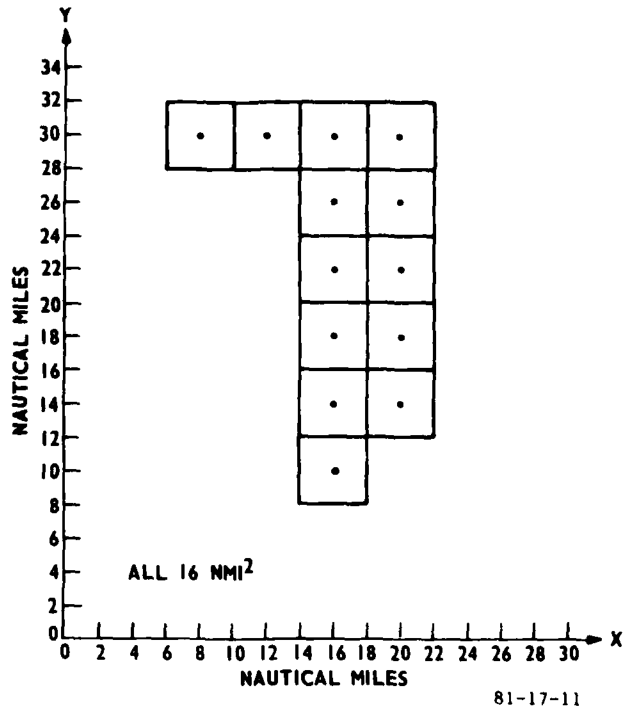


FIGURE 11. ILLUSTRATION OF AREA WEIGHTING FACTORS FOR SCENARIO 2

The points in the center of the areas represent the starting points of the straight-line trajectories. The areas used to weight the results are also given. The (x,y) coordinate system used to express these positions refers to the true positions of the straight-line trajectories relative to the position of the :urning track 2 minutes before the start of the turn. In all scenarios, the starting point of the maneuver remains the same, so that the location of the maneuver relative to the radar does also.

Naturally, as the starting points are located further away from the nuisance alert area boundary, the probability of an alert decreases until a point is reached where the probability of an alert is nil. The areas selected for use in these simulations are chosen to cover a significant portion of the region in which nuisance alerts due to tracking bias for a maneuvering target can expected to occur. The choices are admittedly arbitrary since the nuisance alert area could be extended to cover the area of the straight-line portion of the track after the maneuver is completed. Since the major emphasis in this study is on the improvement of performance in maneuvers, this extension is not considered necessary.

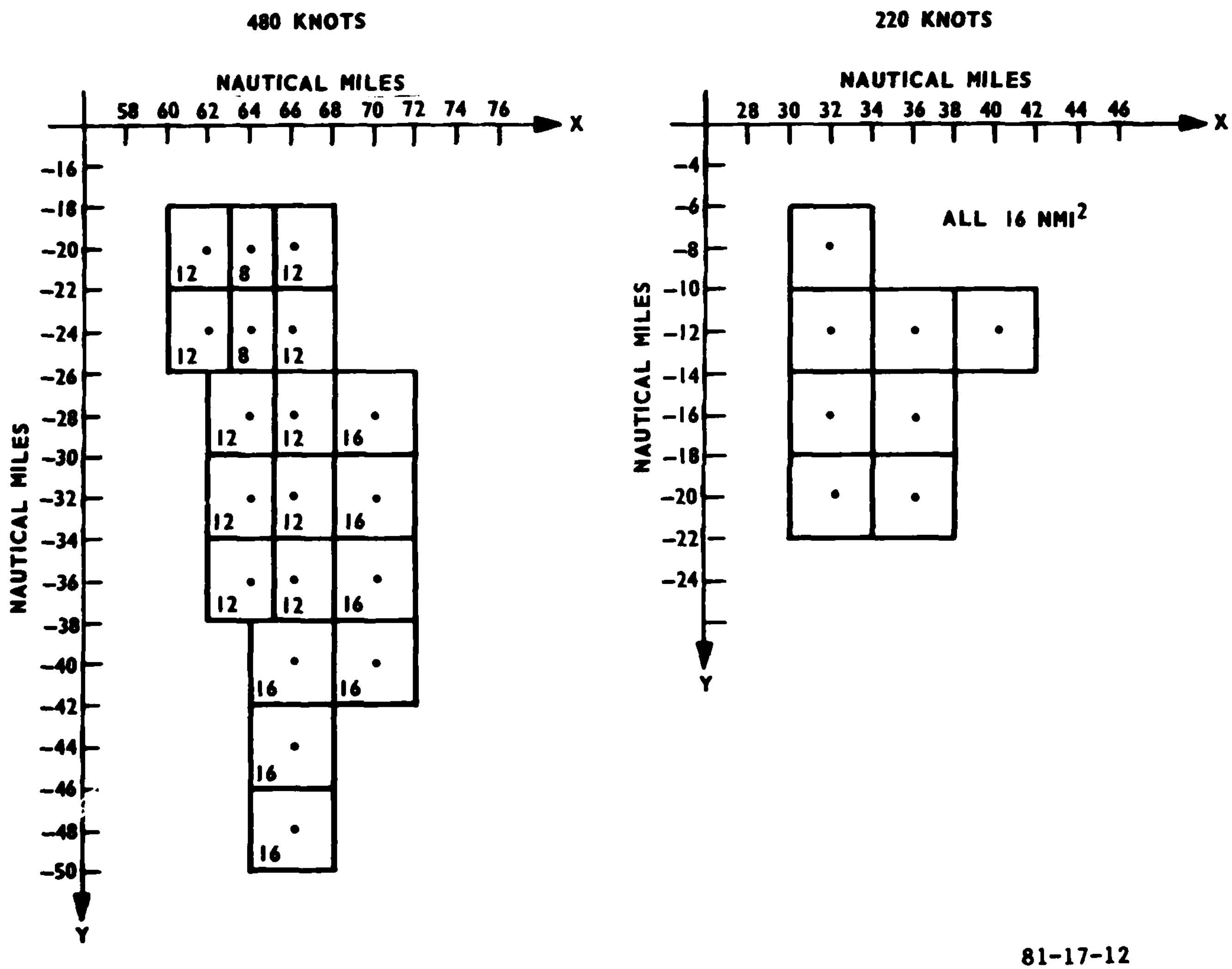


FIGURE 12. ILLUSTRATION OF AREA WEIGHTING FACTORS FOR SCENARIO 3

Note also that no effort is made to superimpose the exact boundary of the nuisance alert area on the areas used for the computations in (33). This is considered an acceptable approach because the computer time required for the evaluation of p(x,y,t) is so great (~ 0.2 hr per point on a Honeywell 66/60) that an extremely fine grid cannot be used.

The detailed simulation results for the nuisance alert area analysis are given in tables 5 to 8, with the results of the evaluation of (33) given in table 9. (The notation N(x,y) is used where it is necessary to cite a specific line of results in table N with a starting point of (x,y).) In general, the results obtained for the maximum percentage of alerts show that the use of track-oriented smoothing parameters, as opposed to the standard smoothing parameters, results in a substantial reduction in the maximum percentage of alerts for scenarios 1 and 3, but a considerable increase in the case of scenario 2. The reason for this increase is thought to be the fact that the speed and heading errors for straight-line tracks in the case of track-oriented smoothing increase considerably, relative to the errors observed for the conventional smoothing parameters, a point which is examined more fully in section 3.4. The increase in the straight-line tracking errors results in relatively more alerts being generated than the reduction of the speed and heading bias errors for the maneuvering track causes them to be decreased.

Considering the performance differences between the various maneuver detection options, the results presented show that for both sets of smoothing parameters in the majority of cases, there is frequently little or no significant difference in performance between the various maneuver detection options. Some notable exceptions, however, do occur. For example, in the case of track-oriented smoothing, the results for 5(64,16) show that the performance of the dynamic search area with delay is significantly better than the MTD with delay maneuver detection option, yet the results for 5(64,26) show exactly the opposite.

In the case of the results for 5(64,20), the fixed search area performance is best. In the case of scenario 2, the performance of the dynamic search area with delay is better in almost all cases. However, it is clear that it is not possible to choose optimal maneuver detectors for each case, and therefore, only an overall average performance measurement is used to select among the various options.

The average performance measure used to summarize the results presented in tables 5 to 8 is the nuisance alert area (see table 9). As found in the case of the individual results given previously, none of the maneuver detection options is uniformly best in all cases. The greatest difference in performance comes from the use of the track-oriented smoothing parameters as opposed to the standard smoothing parameters. For scenario 3, at 480 knots, there is no significant difference between the performance for the various maneuver detection options, while in the case of scenario 3 at 220 knots, and scenario 1, the differences in performance are only marginally significant.

Only the results for scenario 2 can be considered negative in that the nuisance alert area significantly increases with the use of track-oriented smoothing, a change probably due to the increase in the speed and heading errors for straight-line tracks. Thus, even using the nuisance alert area characterization of the various maneuver detection options does not give a clear indication of the option to be selected. As a result, the selection between the various maneuver detection options has to be made assuming some form of relative weighting based on the

TABLE 5. MAXIMUM PERCENTAGE OF ALERTS FOR NUISANCE ALERT AREA ANALYSIS OF SCENARIO 1

Smoothing Parameters:		Standard					Track-Oriented				
Maneuver Detector:		F(N)	D(N)	D(D)	M(D)/D(D)	M(N)/D(D)	F(N)	D(N)	D(D)	M(D)/D(D)	M(N)/D(D)
Initial Position (nmi)	Weight (nmi^2)										
x=62, y=22	4	100.0	100.0	100.0	100.0	100.0	56.2	49.8	90.8	50.2	46.2
y=24	4	98.4	98.4	100.0	99.6	99.6	53.8	44.6	93.6	34.1	31.7
y=26	4	85.9	87.1	98.0	88.4	87.1	38.2	34.5	89.6	18.9	16.1
x=64, y=10	18	96.4	93.6	97.6	97.6	97.6	53.0	35.7	43.0	27.7	31.7
y=16	15	99.6	99.2	99.6	99.6	99.6	39.0	35.7	17.7	48.6	47.8
y=20	9	100.0	100.0	100.0	100.0	100.0	18.9	24.9	27.7	35.3	33.3
y=22	8	99.2	98.0	99.2	98.8	98.4	24.9	24.1	56.6	25.3	28.5
y=24	4	90.4	87.1	93.6	91.6	90.4	21.3	19.3	70.7	13.3	15.3
y=26	6	51.4	35.7	75.9	36.9	32.1	15.7	12.0	64.3	6.0	6.4
y=28	9	5.6	4.4	14.1	3.6	2.8	6.0	8.0	14.1	3.6	2.0
x=66, y=24	4	47.8	33.7	34.5	30.9	31.7	8.0	10.0	10.0	6.4	4.4
x=68, y=10	24	2.8	3.2	4.4	4.4	4.8	14.1	12.0	7.2	4.4	6.0
y=16	20	31.7	26.1	29.7	26.9	24.1	4.0	6.8	5.6	6.4	6.8
y=20	12	32.9	29.7	32.9	18.5	21.7	6.0	6.8	2.0	6.8	5.2
y=24	12	6.8	4.4	5.6	4.4	4.4	4.8	4.8	2.4	2.0	2.4
y=28	20	0.0	0.0	0.4	0.0	0.0	1.6	1.2	0.4	0.4	0.8
x=72, y=6	12	1.2	1.2	0.4	0.8	0.4	3.2	7.2	3.6	3.2	2.8
y=10	24	0.0	0.0	0.0	0.0	0.0	2.0	2.0	0.8	0.4	0.8
y=16	20	0.4	0.4	0.0	0.0	0.0	1.6	1.6	0.8	0.8	1.6
y=20	12	0.0	0.0	0.4	0.0	0.0	1.2	1.6	0.8	1.2	1.2
y=24	24	0.0	0.0	0.4	0.0	0.0	0.8	0.4	0.8	0.4	0.4

TABLE 6. MAXIMUM PERCENTAGE OF ALERTS FOR NUISANCE ALERT AREA ANALYSIS OF SCENARIO 2

Smoothing Parameters:		Standard					Track-Oriented				
Maneuver Detector:		F(N)	D(N)	D(D)	M(D)/D(D)	M(N)/D(D)	F(N)	D(N)	D(D)	M(D)/D(D)	M(N)/D(D)
Initial Position (nmi)	Weight (nmi^2)										
x=8, y=30	16	0.0	0.0	0.0	0.0	0.0	5.2	4.4	2.4	3.2	5.2
x=12, y=30	16	0.0	0.4	0.0	0.0	0.4	14.1	8.4	2.4	4.8	7.6
x=16, y=10	16	0.0	0.0	0.0	0.0	0.0	4.8	0.8	2.4	1.2	2.0
y=14	16	0.0	0.0	0.0	0.0	0.0	7.2	7.6	2.0	5.2	7.6
y=18	16	1.2	1.2	0.0	0.4	0.8	7.6	11.6	1.6	12.0	16.5
y=22	16	11.6	12.0	5.2	10.0	13.3	19.3	23.7	6.8	19.3	28.5
y=26	16	8.0	9.2	3.6	3.6	3.6	23.3	22.1	6.0	11.6	22.1
y=30	16	0.0	0.0	0.0	0.0	0.0	10.8	5.2	2.4	1.2	6.0
x=20, y=14	16	0.0	0.0	0.0	0.0	0.0	1.2	0.8	0.0	0.4	0.4
y=18	16	0.0	0.0	0.0	0.0	0.0	1.6	1.6	0.0	0.8	3.6
y=22	16	0.0	0.0	0.0	0.0	0.0	4.8	4.4	0.4	2.4	3.6
y=26	16	0.0	0.0	0.0	0.0	0.0	7.2	4.8	0.4	1.2	4.8
y=30	16	0.0	0.0	0.0	0.0	0.0	2.4	2.0	0.4	0.4	2.0

TABLE 7. MAXIMUM PERCENTAGE OF ALERTS FOR NUISANCE ALERT AREA ANALYSIS OF SCENARIO 3 WITH A TARGET VELOCITY OF 480 KNOTS

Smoothing Parameters:		Standard					Track-Oriented				
Maneuver Detector:		F(N)	D(N)	D(D)	M(D)/D(D)	M(N)/D(D)	F(N)	D(N)	D(D)	M(D)/D(D)	M(N)/D(D)
Initial Position (nmi)	Weight (nmi^2)										
x=62, y=-20	12	0.4	0.8	0.0	0.8	1.6	9.6	14.1	3.2	16.5	15.3
y=-24	12	90.8	80.3	98.4	80.3	78.7	77.5	51.0	94.8	36.9	34.5
x=64, y=-20	8	0.4	0.4	0.0	0.4	0.4	5.6	8.4	0.8	5.6	8.4
y=-24	8	25.3	16.5	72.3	23.3	24.1	22.5	19.7	69.9	19.3	20.5
y=-28	12	81.1	75.1	70.3	74.3	71.9	13.3	22.5	38.6	28.5	29.7
y=-32	12	92.8	92.0	81.5	93.2	92.8	12.4	21.7	7.6	42.6	41.0
y=-36	12	99.2	98.4	98.8	99.2	99.2	34.1	39.4	13.3	43.4	42.2
x=66, y=-20	12	0.0	0.4	0.0	0.0	0.0	4.0	3.2	0.4	2.0	2.0
y=-24	12	0.8	0.8	2.0	1.6	1.2	5.6	11.6	3.6	6.4	7.2
y=-28	12	30.5	19.7	13.3	14.1	15.3	4.4	15.3	4.8	14.5	14.5
y=-32	12	41.4	43.0	34.9	36.5	38.6	6.4	11.2	3.2	18.1	20.5
y=-36	12	88.0	85.5	88.0	82.7	83.9	12.4	20.1	6.4	19.3	18.5
y=-40	16	88.0	86.7	91.2	86.3	86.7	45.0	30.9	18.5	18.9	18.5
y=-44	16	74.7	74.3	72.3	71.9	72.7	36.9	21.7	18.9	15.3	14.5
y=-48	16	45.4	42.2	43.8	51.0	46.2	7.2	5.6	22.9	9.6	12.0
x=70, y=-28	16	0.4	0.0	0.0	0.4	0.4	0.8	1.2	0.4	1.6	1.2
y=-32	16	1.2	0.8	0.8	0.8	0.8	1.6	3.6	0.4	1.6	2.8
y=-36	16	1.2	1.2	2.4	2.8	3.2	1.2	4.8	0.8	4.0	1.6
y=-40	16	2.4	2.4	2.4	4.0	4.0	1.6	4.8	2.0	2.0	1.6

TABLE 8. MAXIMUM PERCENTAGE OF ALERTS FOR NUISANCE ALERT AREA ANALYSIS OF SCENARIO 3 WITH A TARGET VELOCITY OF 220 KNOTS

Smoothing Parameters:		Standard					Track-Oriented				
Maneuver Detector:		F(N)	D(N)	D(D)	M(D)/D(D)	M(N)/D(D)	F(N)	D(N)	D(D)	M(D)/D(D)	M(N)/D(D)
Initial Position (nmi)	Weight (nmi^2)										
x=32, y=-8	16	1.6	2.0	0.0	0.4	0.8	8.0	19.2	3.2	5.2	12.4
y=-12	16	36.9	26.5	54.6	24.5	27.7	33.7	24.1	51.2	13.7	20.9
y=-16	16	27.5	22.5	21.3	36.9	35.7	10.0	15.5	9.3	19.7	25.3
y=-20	16	6.4	8.0	8.8	10.0	10.4	2.8	7.8	2.8	12.0	11.2
x=36, y=-12	16	0.0	0.0	0.0	0.0	0.0	4.8	6.9	1.2	1.6	3.6
y=-16	16	0.4	0.0	0.0	0.0	0.4	0.8	2.0	0.4	0.4	1.2
y=-20	16	0.0	0.0	0.0	0.0	0.0	0.4	0.4	0.4	0.4	1.6
x=40, y=-12	16	0.0	0.0	0.0	0.0	0.0	0.4	0.4	0.0	0.4	0.8

TABLE 9. NUISANCE ALERT AREAS (NMI^2) FOR THE THREE SCENARIOS IN FIGURE 8

Smoothing Parameters:	Standard					Track-Oriented				
Scenario	F(N)	D(N)	D(D)	M(D)/D(D)	M(N)/D(D)	F(N)	D(N)	D(D)	M(D)/D(D)	M(N)/D(D)
1.	81.7	77.7	84.2	77.6	77.1	35.0	31.5	41.2	27.4	28.2
2.	3.3	3.7	1.4	2.2	2.9	17.5	15.6	4.4	10.2	17.6
3. (480 knots)	99.2	94.1	98.3	94.6	94.2	38.9	39.1	37.0	37.9	37.7
3. (220 knots)	11.7	9.4	13.6	11.5	12.0	9.7	12.2	11.0	8.5	12.3

significance of the various scenarios in the operational environment and the relative cost of each maneuver detection option. This selection process is discussed in the section on conclusions.

3.4 MISCELLANEOUS RESULTS.

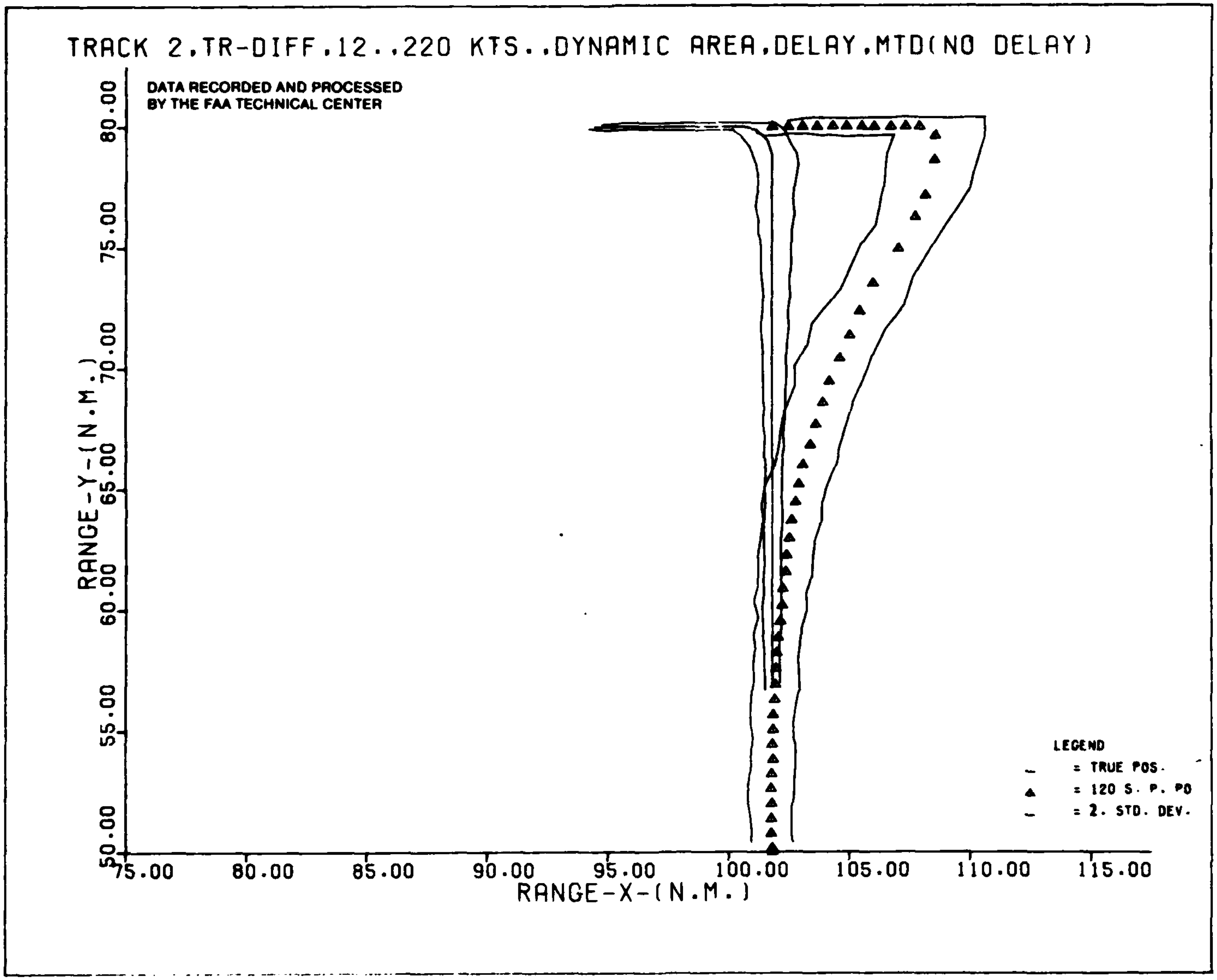
3.4.1 Tracking Performance.

The simulation program used in this study generates a significant amount of statistical data on tracking, most of which has not been presented for the simple reason that it is not directly relevant to the present discussion. In order to compare the results of this study with studies in which only tracking performance was considered, selected simulation output is plotted in figures 13 to 24 to illustrate certain performance features. In all cases, the maneuver detection option used is the MTD with no delay, combined with the dynamic search area with delay (denoted as M(N)/D(D) in the tabular results). The results for this particular maneuver option were arbitrarily chosen for illustration, since the other maneuver detection options produce similar results.

The tracking performance for a 220-knot 90° turn is given in figures 13 to 18, and for a 480-knot turn in figures 19 to 24. In all cases, the results for the standard smoothing parameters are given first, followed by the results obtained using the track-oriented smoothing parameters. The positional data for the tracking algorithm are given in figures 13, 14, 19 and 20 in terms of the present and predicted position, and the statistical variation in the quantities is given in terms of the two standard deviation limits (i.e., the limits plotted are ($\bar{x}-2\sigma_x$, $\bar{y}-2\sigma_y$) and ($x+2\sigma_x$, $\bar{y}+2\sigma_y$). The limits chosen for plotting do not necessarily result in a symmetrical plot. The center line actually represents the true position of the target along with the limits as determined by the standard deviations of the smoothed position. Also given along with the present position is the mean value of the 120-second position prediction denoted by the triangles and the corresponding two sigma limits.

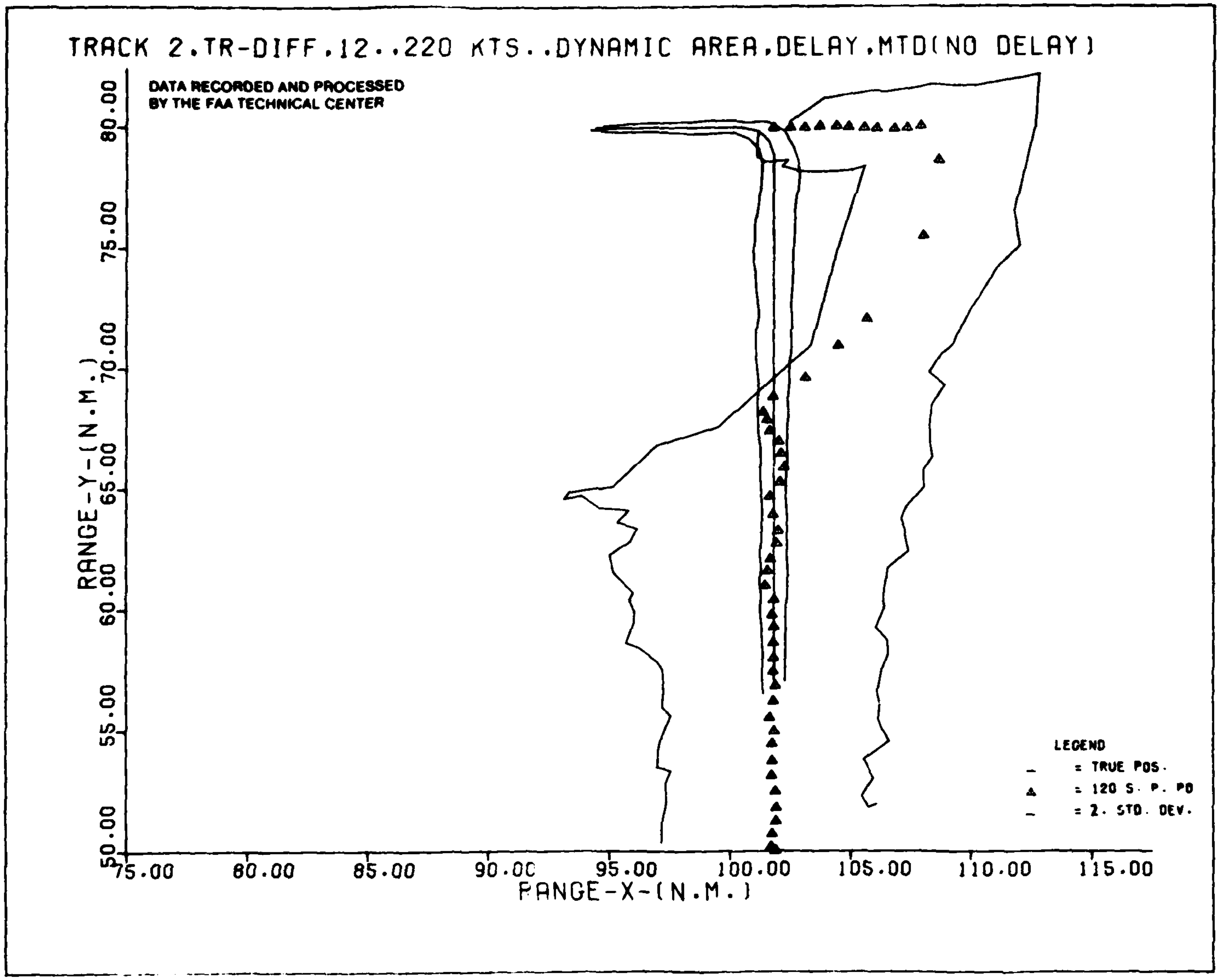
For the conventional smoothing parameters, it is seen that it takes 15 to 20 scans after the start of the turn for the mean value of the 120-second predicted position to return to within the two sigma limits of the present position. For the results obtained using the track-oriented smoothing parameters, it takes only 6 to 9 scans to obtain the same level of reduction in the transient bias error of the 120-second position prediction. However, as is obvious by comparing figure 13 with 14 and 19 with 20, the penalty paid for the more rapid response of the tracking algorithm to a maneuver is a considerable increase in random errors in both the smoothed and predicted positions. For example, the distance between the two sigma limits of the 120-second predicted position at the end of the simulation, approximately a steady-state condition, is about 1.5 nmi using standard smoothing parameters, but 8 nmi for the track-oriented smoothing parameters.

In the 480-knot case the equivalent values are slightly less, but the relative comparison between the results for the standard and track-oriented smoothing parameters remains the same. Note that in the case of track-oriented smoothing at both speeds, there is a tendency for the output of the tracking algorithm to oscillate, an occurrence more prevalent at 220 knots than at 480 knots, and not present with the standard smoothing parameters.



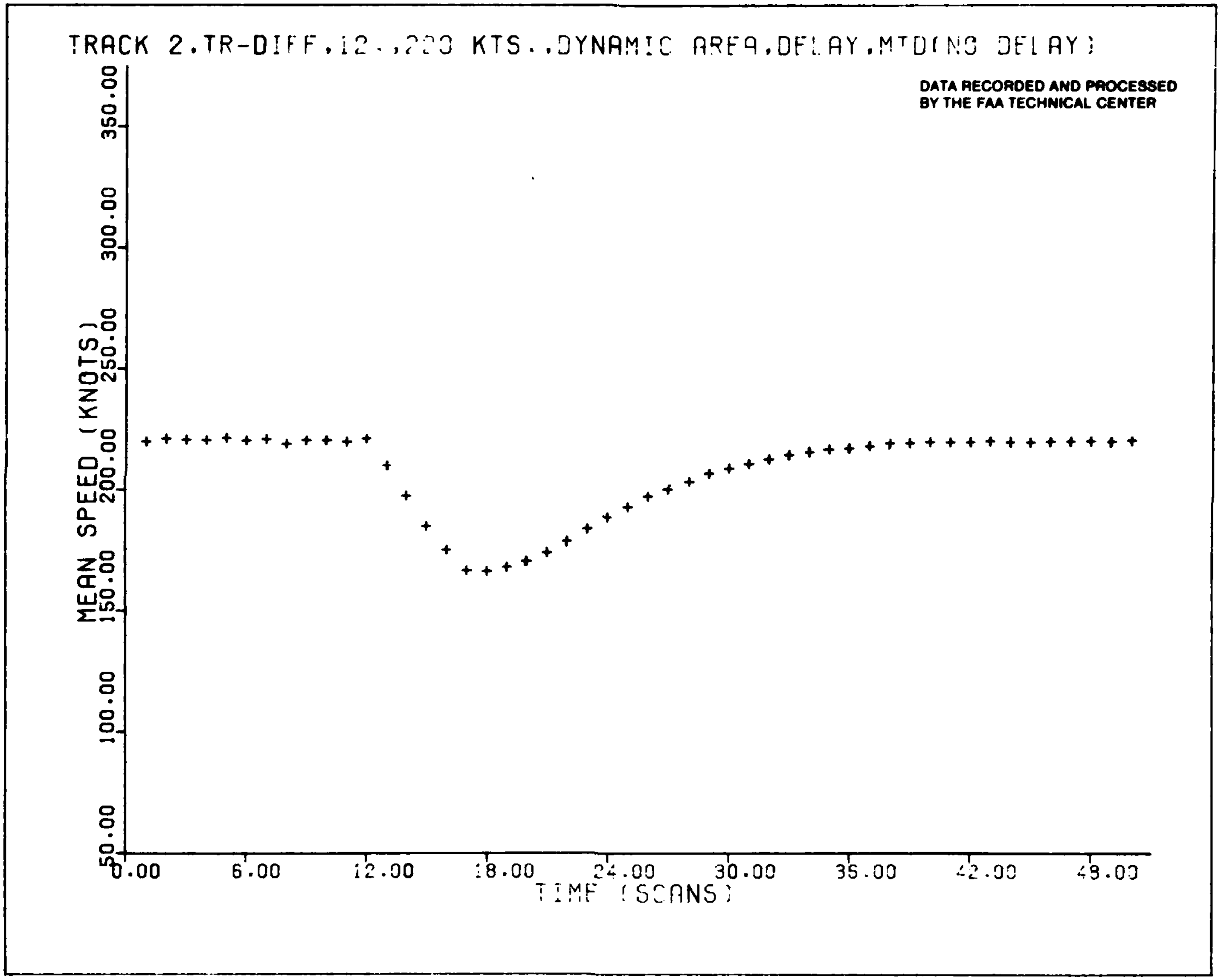
81-17-13

FIGURE 13. PREDICTED POSITION AT 220 KNOTS WITH STANDARD SMOOTHING PARAMETERS



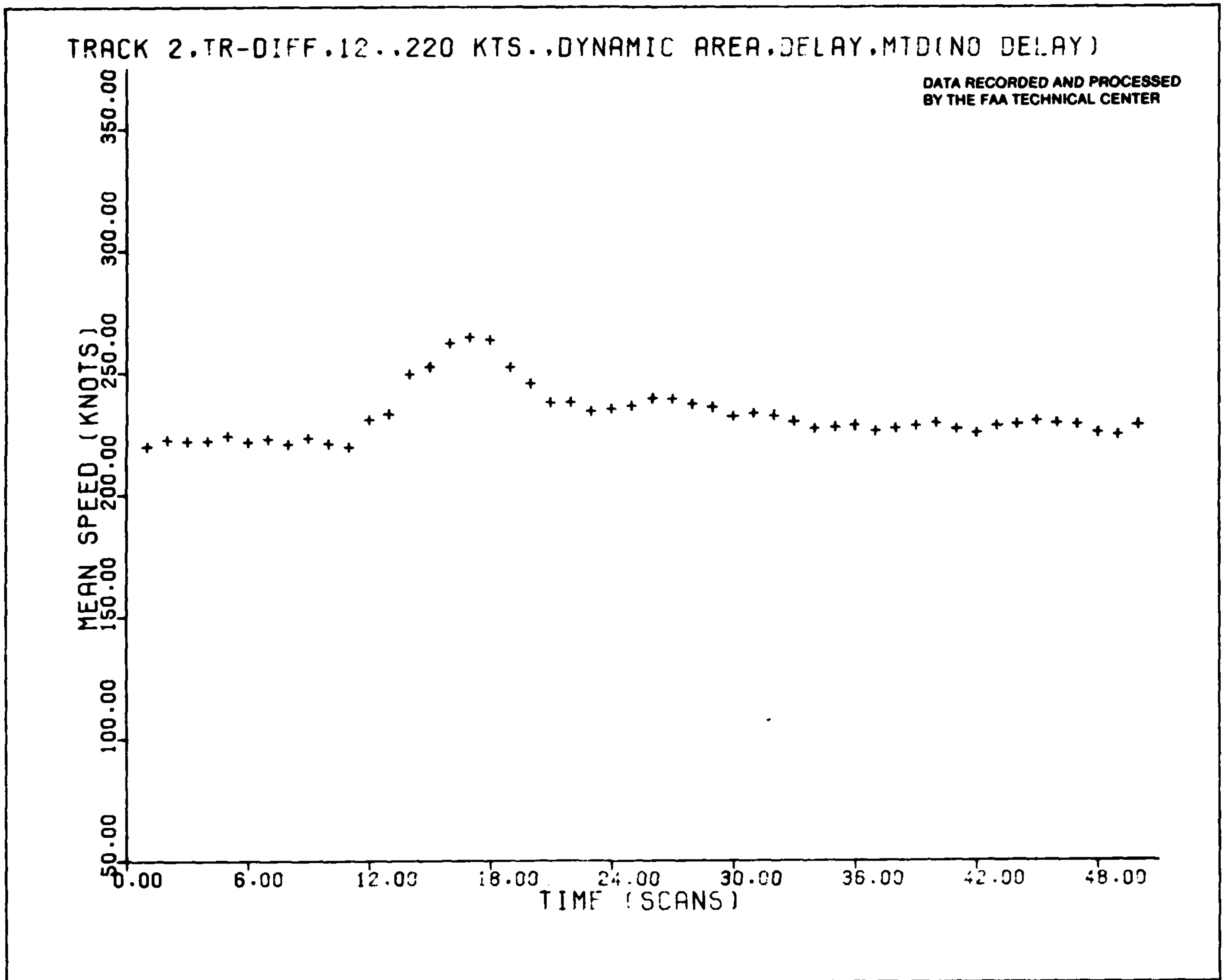
81-17-14

FIGURE 14. PREDICTED POSITION AT 220 KNOTS WITH TRACK-ORIENTED SMOOTHING PARAMETERS



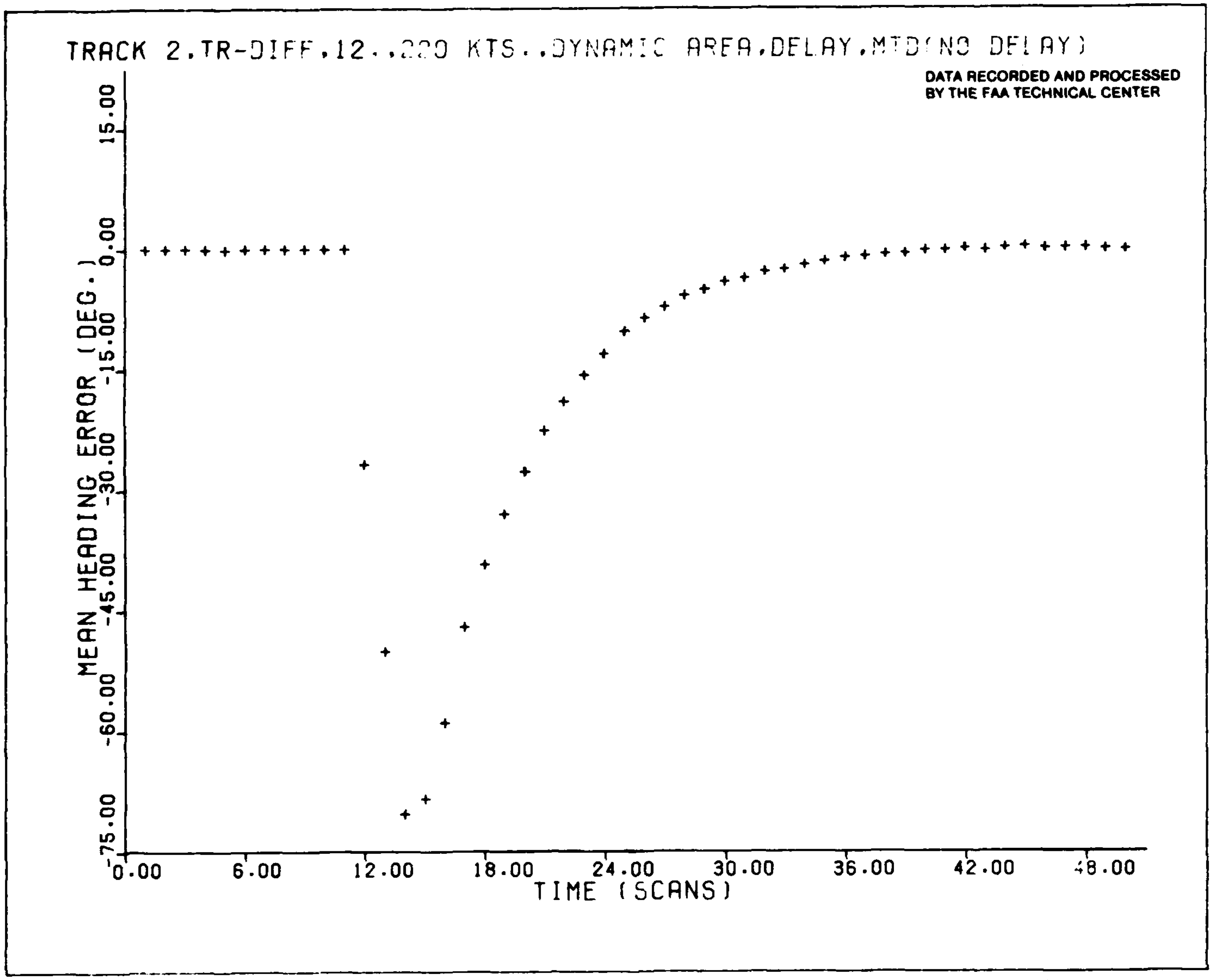
81-17-15

FIGURE 15. MEAN SPEED AT 220 KNOTS WITH STANDARD SMOOTHING PARAMETERS



81-17-16

FIGURE 16. MEAN SPEED AT 220 KNOTS WITH TRACK-ORIENTED SMOOTHING PARAMETERS



81-17-17

FIGURE 17. MEAN HEADING ERROR AT 220 KNOTS WITH STANDARD SMOOTHING PARAMETERS

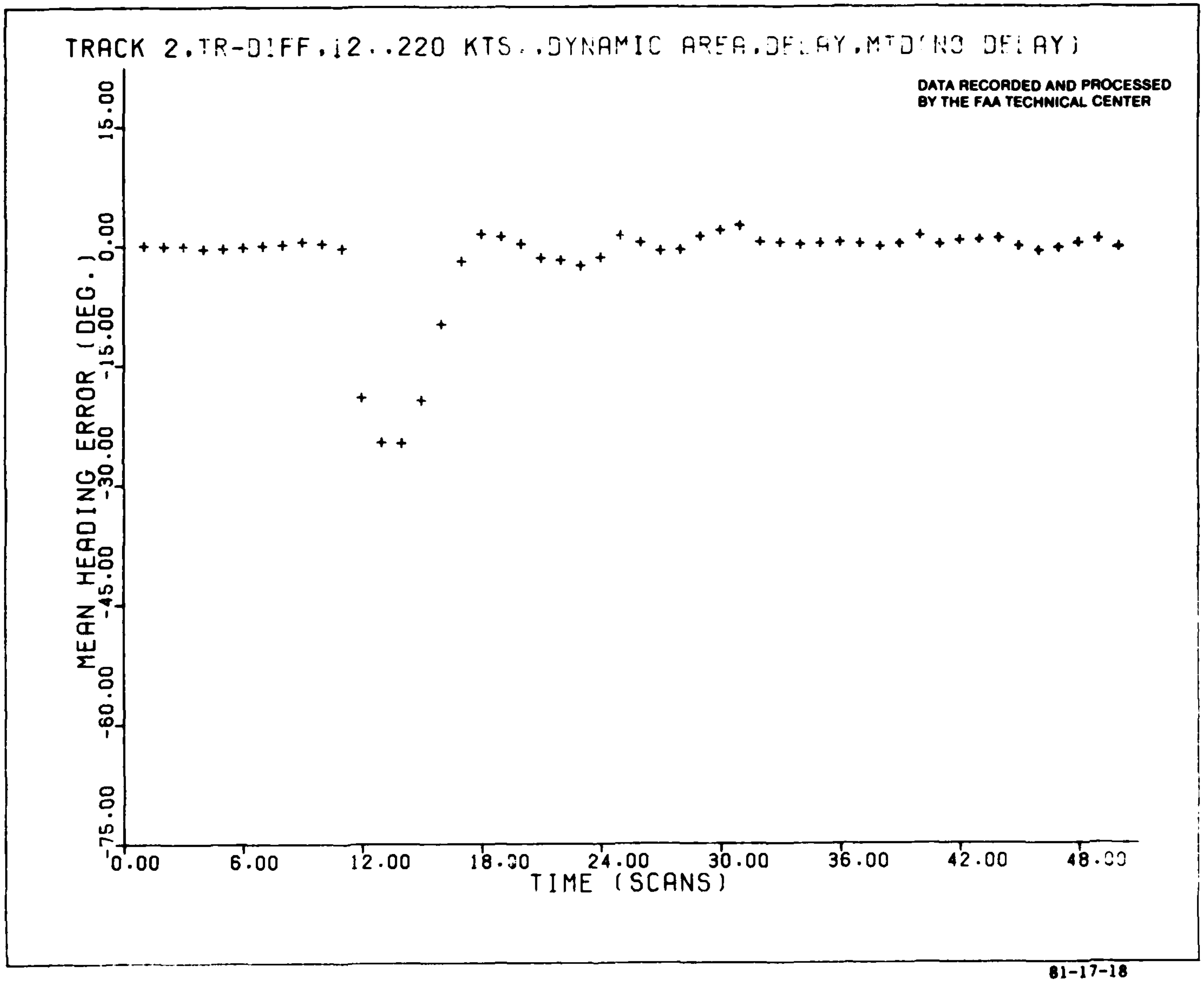
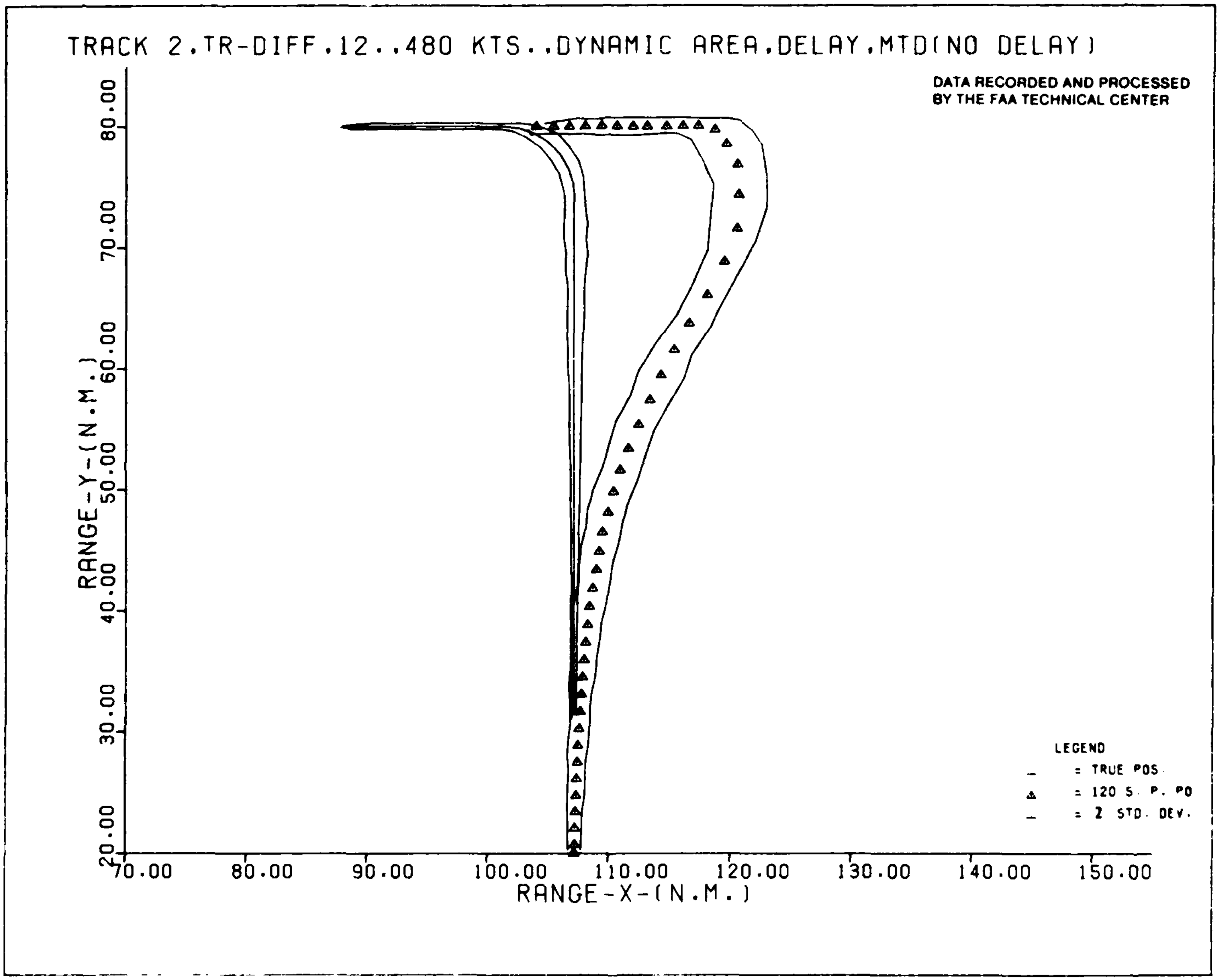
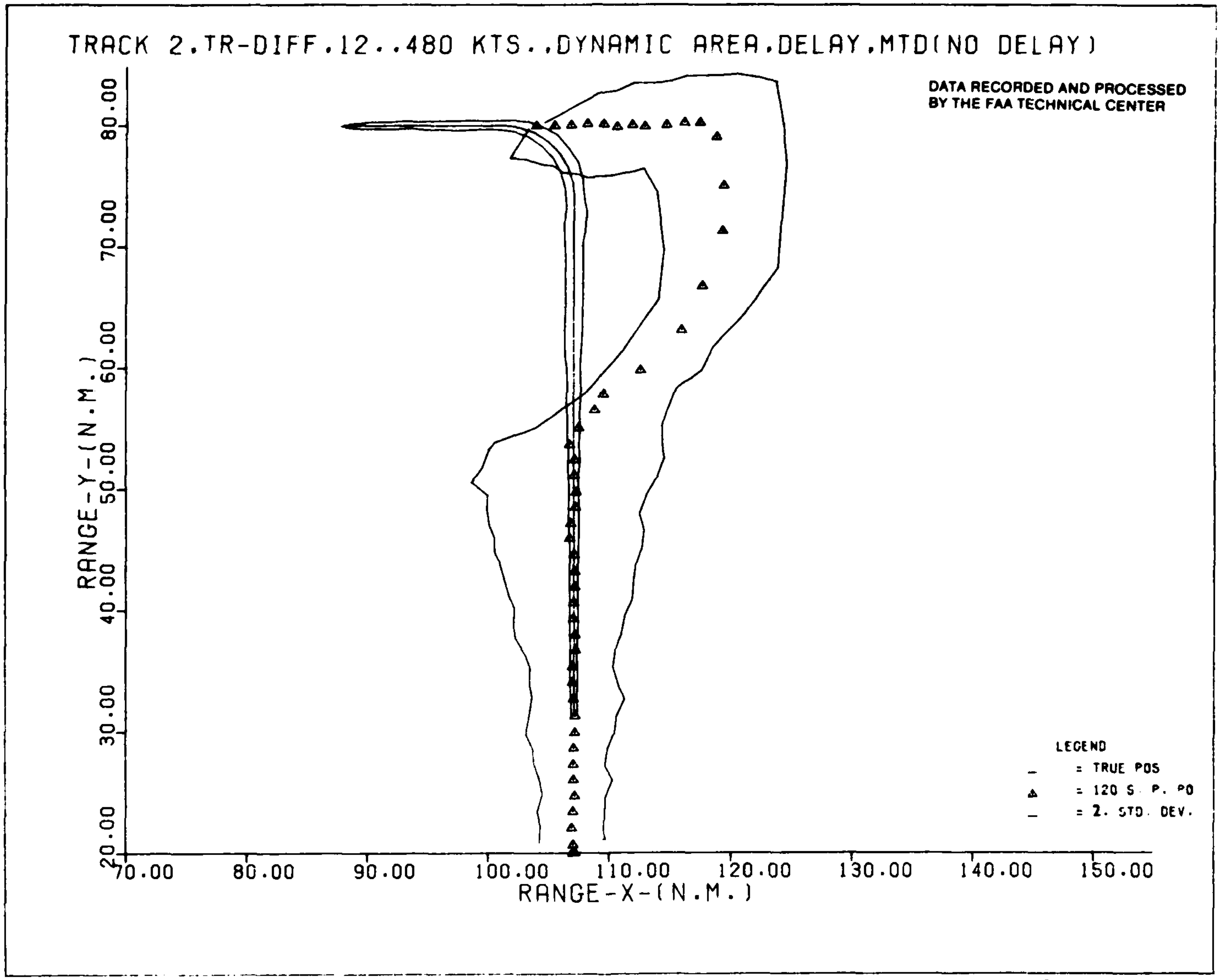


FIGURE 18. MEAN HEADING ERROR AT 220 KNOTS WITH TRACK-ORIENTED SMOOTHING PARAMETERS



81-17-19

FIGURE 19. PREDICTED POSITION AT 480 KNOTS WITH STANDARD SMOOTHING PARAMETERS



81-17-20

FIGURE 20. PREDICTED POSITION AT 480 KNOTS WITH TRACK-ORIENTED SMOOTHING PARAMETERS

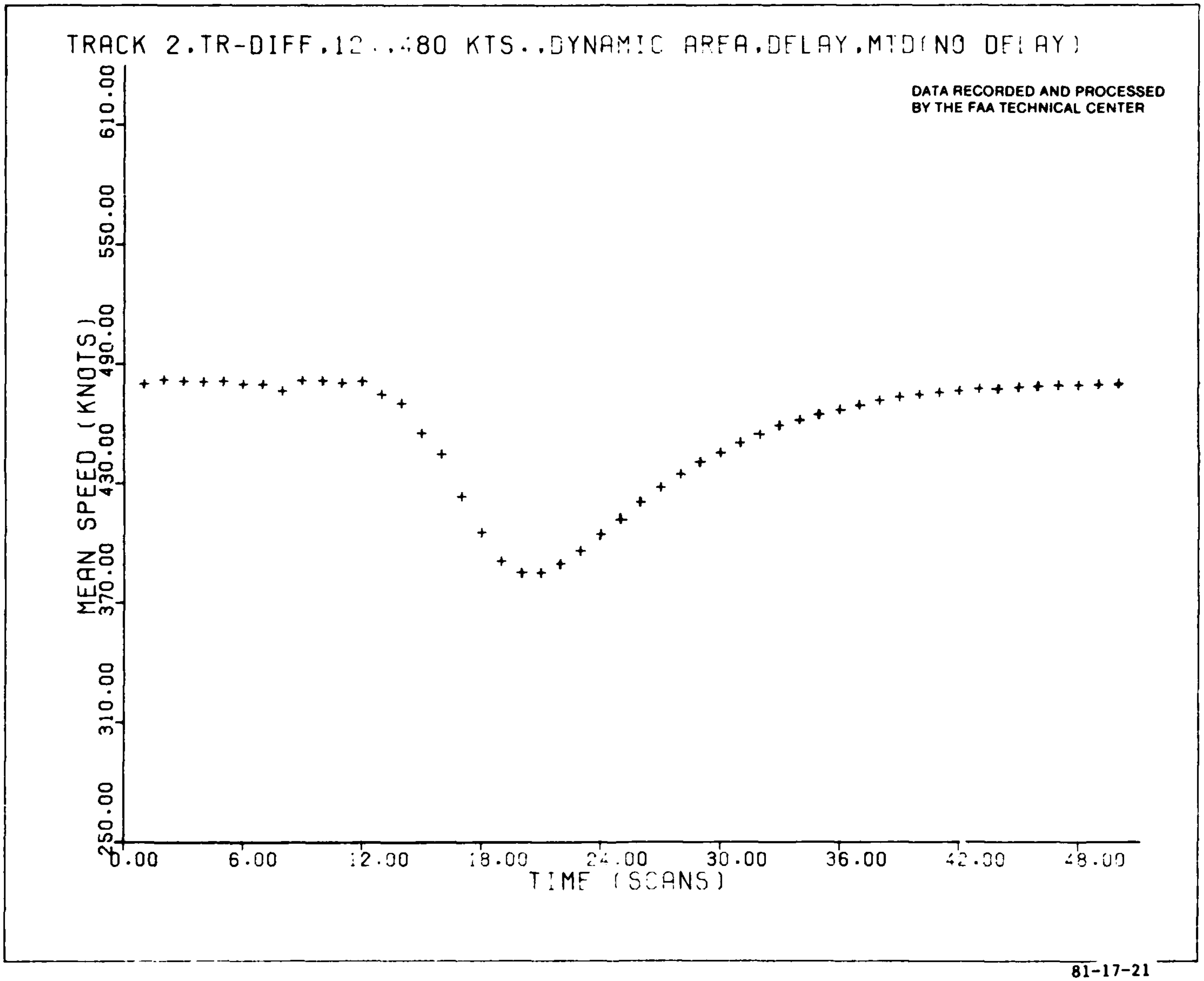
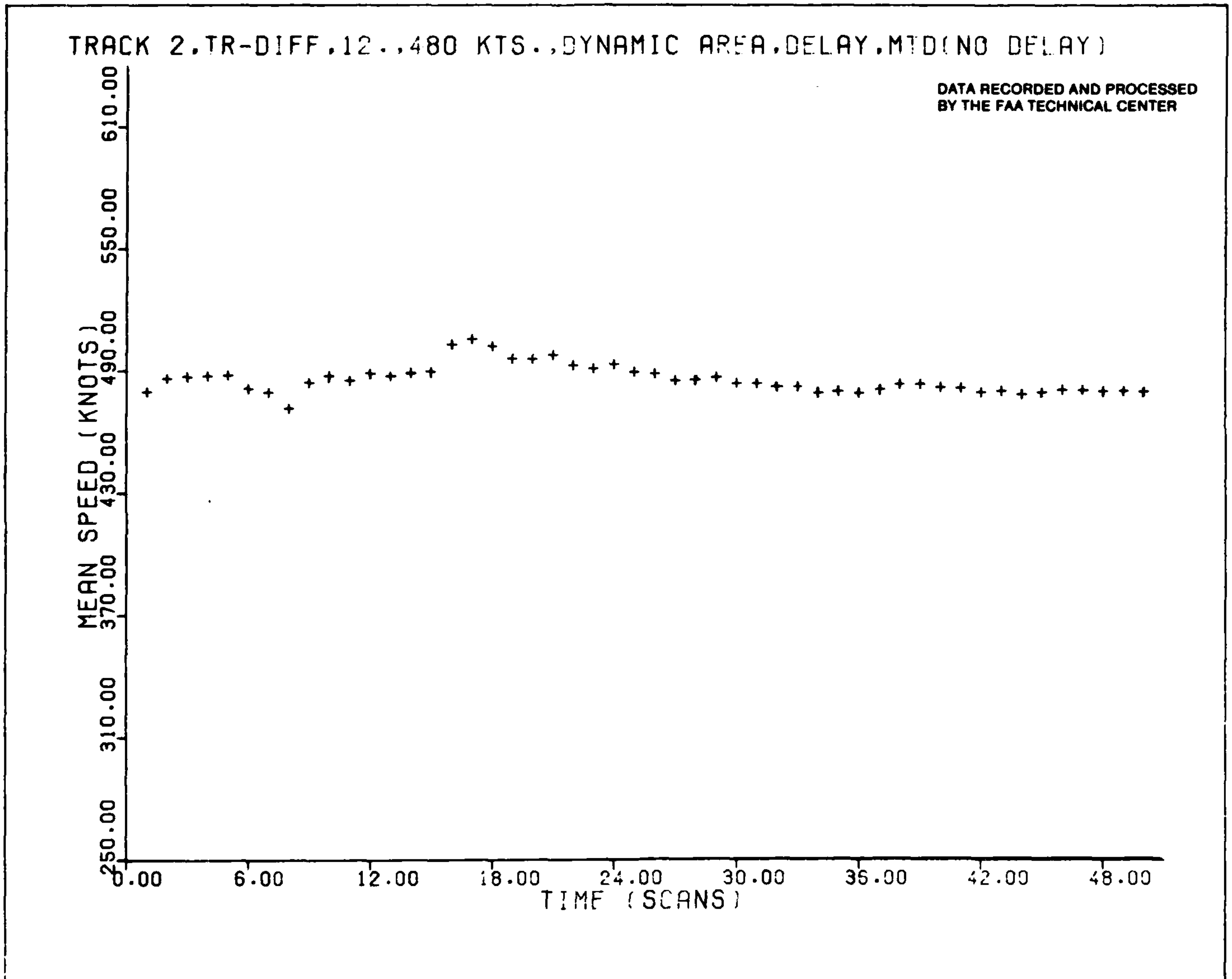


FIGURE 21. MEAN SPEED AT 480 KNOTS WITH STANDARD SMOOTHING PARAMETERS



81-17-22

FIGURE 22. MEAN SPEED AT 480 KNOTS WITH TRACK-ORIENTED SMOOTHING PARAMETERS

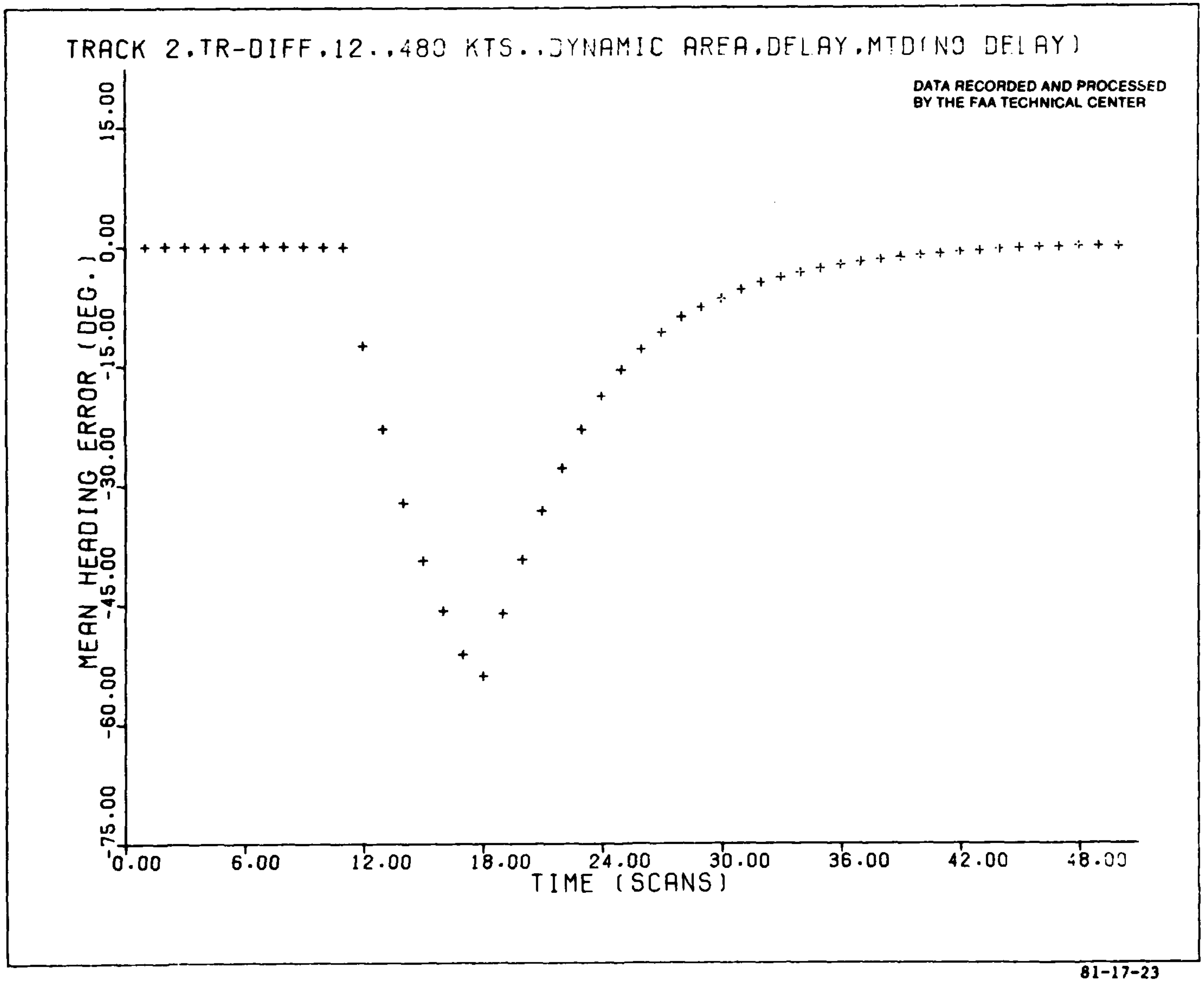


FIGURE 23. MEAN HEADING ERROR AT 480 KNOTS WITH STANDARD SMOOTHING PARAMETERS

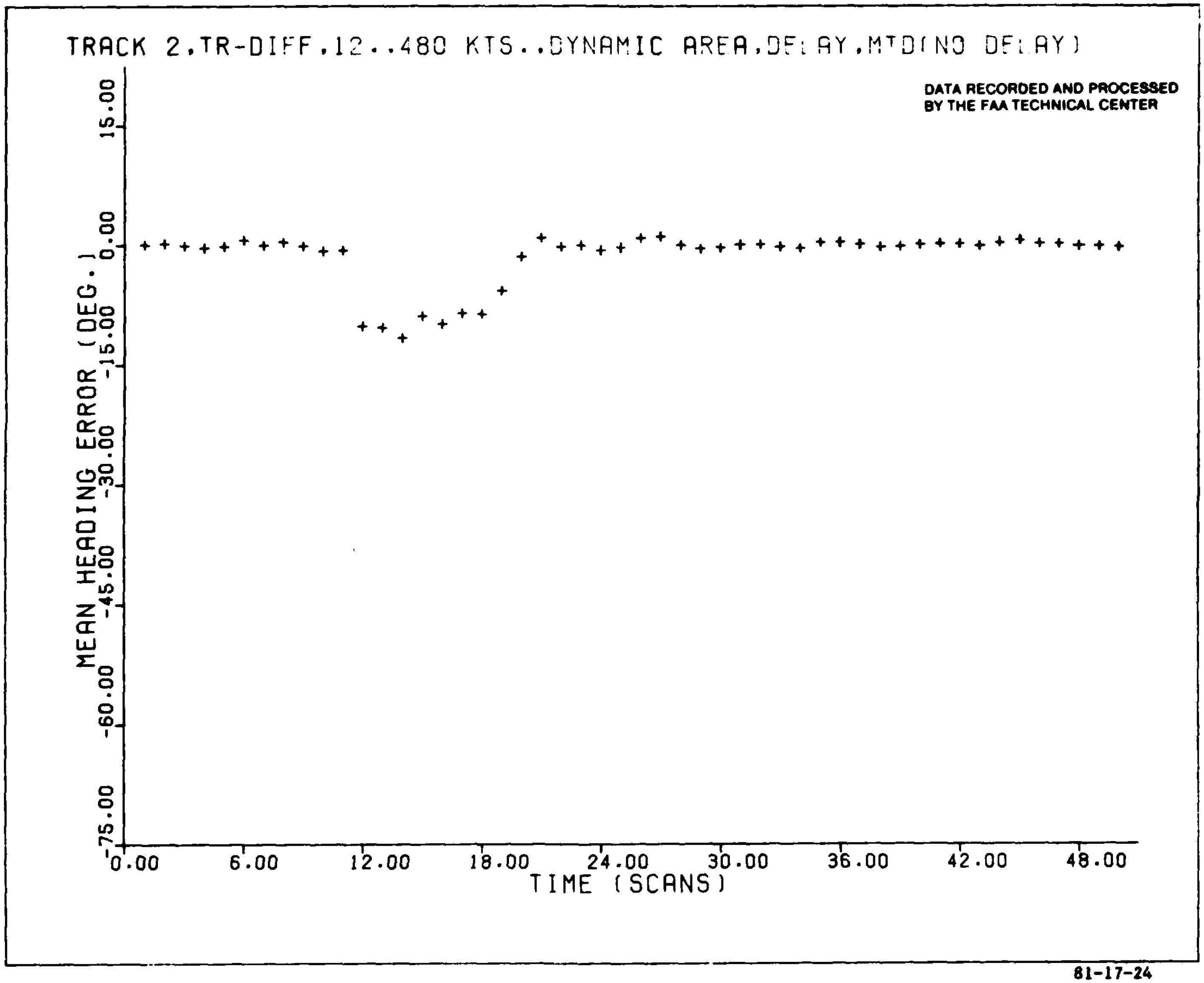


FIGURE 24. MEAN HEADING ERROR AT 480 KNOTS WITH TRACK-ORIENTED SMOOTHING PARAMETERS

Also given in each case are plots of the mean heading error and mean speed. The results in both cases show trends quite similar to those obtained for the position data: large reduction in the bias error during maneuvers, and a tendency for the tracking algorithm to oscillate using track-oriented smoothing that is more pronounced at 220 knots than at 480.

Also given in each case are plots of the mean heading error and mean speed. The results in both cases show trends quite similar to those obtained for the position data: large reduction in the bias error during maneuvers, and a tendency for the tracking algorithm to oscillate using track-oriented smoothing that is more pronounced at 220 knots than at 480.

The increase in the speed and heading errors resulting from the use of track-oriented smoothing is sufficient to warrant a more exact assessment to ascertain the magnitude of the problem. The results of this assessment are given in table 10 in terms of the standard deviation in speed, σ_s, in knots, and heading, σ_H, in degrees, for the straight-line track in the turn onto a different track scenario at 480 knots with a 12-nmi separation (the warning time results were previously given in table 3). The results obtained confirm the magnitude of the increase in the speed and heading errors.

The use of track-oriented smoothing with specified parameters results in speed errors 3 to 4 times those for the standard parameters. Heading errors are 6 to 7 times greater. The increase in the speed error for track-oriented smoothing using a dynamic search area with a one-scan delay is only 56% compared to the fixed search area with the standard smoothing parameters. This increase is considerably less than the increases observed using the MTD, clearly the worst results in this aspect.

It would be desirable to reduce the magnitude of the speed and heading errors in the 120-second position prediction because they approach the separation standards, and it is questionable whether such errors would be operationally acceptable. One obvious method for reduction of the speed and heading errors in the case when the MTD is used is to raise the threshold specifying when a maneuver is detected by the MTD. Such a change would reduce the number of erroneous maneuver declarations and reduce the number of times the large search area smoothing constants are used. The results in table 10 for a MTD threshold of 10 show that some significant reductions in the speed and heading errors are achieved by this change. In fact, for the standard smoothing parameters, σ_s and σ_H for M(D)/D(D) are now about at the same level as the baseline results for the fixed search area. However, for the track-oriented smoothing parameters the results are still several times larger than the baseline results.

One question that naturally might be raised in this case is whether or not the increase in the MTD threshold will affect the warning time observed with the system. The warning times for the various maneuver detection options are denoted by $T_{4.8}$ and $T_{2.8}$, where the value of the subscript denotes the value of the SPMB and SPPB parameters in the Conflict Alert algorithm. All previous results were obtained with a value of 4.8 and these are the only ones presently of interest. Comparing the warning times for a threshold of 7 with those for a threshold of 10, it is seen that there are no significant impacts on the warning time performance of the algorithm.

TABLE 10. ILLUSTRATION OF SPEED ERRORS, HEADING ERRORS, AND WARNING TIMES FOR DIFFERENT PARAMETER VALUES IN THE 480-KNOT, 12-NMI SEPARATION SCENARIO

Smoothing Parameters:		Standard					Track-Oriented				
Maneuver Detector:		F(N)	D(N)	D(D)	M(D)/D(D)	M(N)/D(D)	F(N)	D(N)	D(D)	M(D)/D(D)	M(N)/D(D)
MTD Threshold=7	σ_s	9.32	13.60	7.89	14.91	16.44	25.51	48.68	14.55	53.09	56.46
	σ_H	0.50	0.68	0.44	0.82	0.95	3.08	6.26	1.79	6.54	6.97
	$T_{4.8}$	45.3	45.5	45.1	45.8	45.8	50.4	55.0	47.7	57.4	58.2
	$T_{2.8}$	39.8	40.4	39.8	40.3	40.7	43.1	47.9	39.7	50.9	52.0
MTD Threshold=10	σ_s				9.86	12.25				29.73	44.09
	σ_H				0.51	0.69				3.48	6.13
	$T_{4.8}$				46.2	45.9				53.8	55.6

3.4.2 Parameter Changes In Conflict Alert.

Just as an increase in the MTD threshold is a logical means to reduce the speed and heading errors resulting from erroneous application of the large search area smoothing parameters, the use of a smaller alert generation region (defined by SPMB and SPPB) is a logical means to reduce the size of the nuisance alert area. Reducing the SPMB and SPPB parameter values will make the Conflict Alert algorithm less sensitive, reducing the warning time, but, this rate of reduction will hopefully be significantly less than that in the nuisance alert area.

Accordingly, in an attempt to devise an alternative technique for reducing the nuisance alert area, the values of the SPMB and SPPB parameters are reduced from 4.8 to 2.8 nmi, which is a substantial but not unreasonable reduction. Note, that the controller is not required to control traffic so that it will appear that targets will be separated in the future, and application of the current separation requirements to a future event is unnecessary. The alert generation region defined using predicted positions should be dependent on the ability of the sensor data and tracking algorithm to predict the future position of a target rather than on operational flight rules meant to maintain the current separation of the target with human intervention, when necessary.

The results in table 10 show that the reduction in the parameter value from 4.8 to 2.8 results in a reduction in the warning time of approximately one-half of a tracking cycle. By the criterion adopted previously for the significance of warning time differences, the differences in the results for 4.8 and those for 2.8 are so small as to be unnoticeable in an operational environment.

The nuisance alert area results for the modified Conflict Alert algorithm parameters are given in tables 11 and 12 for scenario 3, which was the only scenario used for these tests. Comparing the results in table 11 with those in table 9, it is seen that in the case of the 480-knot simulation of scenario 3, the change in the SPMB and SPPB parameters values usually results in a reduction in the size of the nuisance alert area by almost a factor of 4 for both the standard and track-oriented smoothing parameter values. With this change in parameter values, the nuisance alert areas for the standard smoothing parameters are less than those for track-oriented smoothing when using the 4.8-nmi alert generation region.

In the case of the results for the 220-knot simulation of scenario 3, given in table 12, the reduction in the size of the nuisance alert area for the standard smoothing parameters are even more significant, ranging from a factor of about 10 to 30. For the 220-knot simulation in the case of track-oriented smoothing, the reductions in the nuisance alert areas are not nearly as large. Consequently, the combination of both changes (track-oriented smoothing and the reduction in SPMB and SPPB) results in performance that is significantly worse than that observed with the reduction in the SPMB and SPPB parameters alone. The results obtained with the changes in the SPMB and SPPB parameter values demonstrate an extreme sensitivity in the nuisance alert area to changes in the design of the Conflict Alert algorithm. As a result, it may be possible to develop alternatives to the use of the MTD data based on changes in the algorithm per se, rather than relying on additional data sources of questionable accuracy.

TABLE 11. NUISANCE ALERT AREA ANALYSIS OF SCENARIO 3 WITH A TARGET VELOCITY OF 480 KNOTS AND SPMB=SPPB=2.8 NMI

Smoothing Parameters:		Standard					Track-Oriented				
Maneuver Detector:		F(N)	D(N)	D(D)	M(D)/D(D)	M(N)/D(D)	F(N)	D(N)	D(D)	M(D)/D(D)	M(N)/D(D)
Initial Position (nmi)	Weight (nmi²)										
x=62, y=-20	12	0.0	0.0	0.0	0.4	0.4	4.4	5.6	0.8	4.0	7.2
y=-24	12	30.1	26.5	32.9	19.7	14.5	25.7	20.1	32.1	16.1	14.5
x=64, y=-20	8	0.0	0.0	0.0	0.0	0.0	2.0	2.8	0.4	1.6	1.6
y=-24	8	2.4	0.8	1.6	0.8	0.0	3.2	7.6	3.6	6.0	5.2
y=-28	12	15.7	12.4	19.3	16.5	18.5	4.0	10.8	15.3	10.4	13.7
y=-32	12	27.3	24.5	24.1	18.9	21.3	6.0	10.0	2.4	18.5	21.3
y=-36	12	79.9	77.5	81.9	78.3	79.9	8.0	16.1	5.2	14.5	15.3
x=66, y=-20	12	0.0	0.0	0.0	0.0	0.0	0.4	0.8	0.0	0.8	0.4
y=-24	12	0.0	0.0	0.0	0.0	0.0	1.6	2.0	0.8	2.4	1.2
y=-28	12	0.4	1.2	2.0	1.2	1.2	1.6	3.6	2.4	4.0	5.2
y=-32	12	4.4	8.4	5.2	6.0	4.4	2.0	5.6	0.4	7.2	9.6
y=-36	12	22.9	26.1	22.5	25.3	23.7	4.8	8.8	2.4	4.4	4.8
y=-40	16	18.1	19.7	23.7	22.9	22.5	12.0	9.2	4.8	5.2	6.8
y=-44	16	10.4	12.0	9.6	11.6	12.0	10.0	5.6	4.4	4.0	5.6
y=-48	16	3.2	2.8	2.0	3.6	4.0	2.4	0.8	5.2	1.6	3.2
x=70, y=-28	16	0.0	0.0	0.0	0.0	0.0	0.4	0.4	0.0	0.4	0.0
y=-32	16	0.0	0.0	0.0	0.0	0.0	0.0	1.6	0.4	0.4	1.2
y=-36	16	0.0	0.0	0.4	0.0	0.0	0.0	0.8	[illegible]	1.2	0.4
y=-40	16	0.0	0.0	0.0	0.0	0.0	0.4	0.8	0.8	0.4	0.4
Nuisance Alert Area (nmi²)		26.9	26.8	28.4	26.1	25.8	11.5	13.9	10.2	12.6	14.5

TABLE 12. NUISANCE ALERT AREA ANALYSIS OF SCENARIO 3 WITH A TARGET VELOCITY OF 220 KNOTS AND SPMB=SPPB=2.8 NMI

Smoothing Parameters:		Standard					Track-Oriented				
Maneuver Detector:		F(N)	D(N)	D(D)	M(D)/D(D)	M(N)/D(D)	F(N)	D(N)	D(D)	M(D)/D(D)	M(N)/D(D)
Initial Position (nmi)	Weight (nmi^2)										
x=32, y=-8	16	0.0	0.4	0.0	0.0	0.0	4.0	7.8	1.2	1.6	
y=-12	16	2.0	2.8	0.8	1.6	1.2	6.0	11.0	2.8	2.0	[illegible]
y=-16	16	1.2	1.6	1.2	1.2	1.2	2.4	5.3	0.8	5.2	6.0
y=-20	16	0.0	0.0	0.0	0.0	0.0	0.4	2.5	0.4	4.0	3.6
x=36, y=-12	16	0.0	0.0	0.0	0.0	0.0	1.2	1.6	0.4	0.0	0.8
y=-16	16	0.0	0.0	0.0	0.0	0.0	0.0	0.8	0.4	0.0	0.0
y=-20	16	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4
x=40, y=-12	16	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.4	0.4
Nuisance Alert Area (nmi^2)		0.5	0.8	0.3	0.4	0.4	2.3	4.6	1.0	2.1	3.3

The reduction of the size of the alert generation region is accompanied by an increase in the potential area of nuisance alerts. Consequently, some alerts previously defined as true alerts are now false alerts, so that to be strictly correct, some additional simulations should be run closer to the boundary of the nuisance alert area. This would result in an increase in the nuisance alert area for the reduced alert generation region. However, in order to avoid complicating the analysis and to allow a comparison under exactly the same condition, only the initial starting points already selected are used in this case.

4. SUMMARY AND CONCLUSIONS.

The objective of this study was to determine if Speed Interpolation Numbers (SIN's), produced by the Moving Target Detector (MTD), could be used to improve the performance of the National Airspace System (NAS) en route tracking algorithm, which uses position measurements supplied by the Air Traffic Control Radar Beacon System. An improvement in tracking performance was expected to be reflected in an improvement in the performance of the Conflict Alert algorithm in the form of a reduction in false alerts and an increase in warning time to hazardous situations. Because the additional computational resources available for use by tracking modifications are extremly limited, the technical approaches examined for use in this study were restricted to techniques that could be implemented with minor computer program modifications.

Given these circumstances, it was determined that the only practical application of the SIN's would be to discriminate, as a maneuver detector, between targets on straight-line trajectories and maneuvering targets. This maneuver detection function was performed in the study by subjecting the scan-to-scan difference in the SIN's to a threshold that indicated a maneuver by sensing the change in the radial velocity. The initial results on the use of the SIN's in this manner, given in section 2.4, were sufficiently encouraging to warrant further examination. However, it must be noted that all results in this study were based on the assumption of a specific level of accuracy in the SIN's that, if not achieved, would invalidate the results.

Once a maneuver was detected, either by employing the MTD or by the standard approach in which the track datum deviation falls in the large search area, the smoothing constants had to be sufficiently large to reduce the bias that develops in speed and heading as targets maneuver. For this purpose, the track-oriented smoothing feature was used and the cross-track deviation was weighted more heavily than the along-track deviation so that it followed the maneuver more closely.

In order to determine if it is worthwhile to use the MTD data in the proposed manner, a program was developed to simulate the operation of the tracking and Conflict Alert algorithms (section 3.1). Simplifications were made in the program mainly in the area of processing in a multisensor environment. In addition, all computations were performed using floating-point arithmetic for the smoothing and prediction processes in the tracking algorithm, whereas the operational program uses fixed-point arithemetic which introduces a greater level of computational error. In order to simplify the comparison between the various modifications to the tracking algorithm, the same sequence of random numbers was used in each case so that any differences observed could be attributed to a specific cause.

Because the MTD must be used in conjunction with some other form of maneuver detector serving as back-up in case the MTD data are missing or does not detect the maneuver, a total of five possible maneuver detection options were examined: (1) a fixed search area, as is presently used, (2) a dynamic search area, (3) a dynamic search area with a one-scan delay in the use of the large search area smoothing constants, (4) MTD and dynamic search area, both with a one-scan delay, and (5) MTD with no delay combined with the dynamic search area with delay.

A point which should be noted before examining the simulation results is that there are many other factors which influence the performance of the tracking and Conflict Alert algorithms that were not considered in this study. If the influence of these other factors is significant, then the performance results observed in this study may not be found in an operational environment. In particular, this study was limited to the horizontal plane; the vertical aspect of tracking was ignored completely.

However, deficiences in the performance of the vertical tracker have already been identified (reference 14), so that if the impact of the vertical tracker actually is significant, the modifications considered in this study will not have the expected impact. In addition, the tracking modifications considered in this study were intended to improve performance for maneuvering targets. If the majority of alerts generated are for targets on straight-line trajectories, then no significant operational improvements will be found.

For each of the five maneuver detection options under consideration, two sets of smoothing constants were used: the standard parameter values and those for track-oriented smoothing. A total of ten different maneuver detection options and smoothing parameter value combinations were evaluated in all cases. Various scenarios, described in sections 3.2 and 3.3, were created to test the performance of the tracking and Conflict Alert algorithms under these ten combinations. The first set of scenarios were designed to measure the warning time provided in various critical situations. The performance statistics obtained for this case, in terms of the mean value of the warning time before collision, have been given in table 3. The warning time results represent a measure of the positive aspect of system performance.

The results of these simulations show that in almost all cases there was no significant difference in performance between the various maneuver detection options or between the results with the standard or track-oriented smoothing parameters. In examining these results, it must be remembered that the simulation process did not model events that occur on a temporal scale of less than one tracking cycle. As a result, any differences less than 10 or even 20 seconds (1 or 2 tracking cycles) can be ignored since it is highly questionable whether such differences would even be noticeable, much less measurable, in an operational environment.

In only one scenario were differences on the order of 30 to 40 seconds obtained uniformly for the track-oriented smoothing parameters as compared to the standard parameters. In this case alone is an improvement in performance likely to be observed in an operational environment, but this improvement would only be on the order of 1 or 2 tracking cycles. Since the performance for this particular scenario was already acceptable, this represented no net gain in performance. As a result, it is concluded that there are no significant differences in the warning time results due to the use of any of the maneuver detection options considered or due to the smoothing parameter values which have been examined in this study.

In addition to the mean warning time, the standard deviation in the warning time was also examined. The results show that the variability in the warning time for track-oriented smoothing was significantly greater than that observed with the standard smoothing parameter values. While this variability in performance is not reflected in the mean value statistics, it does indicate that significantly larger extremes in performance will be observed with track-oriented smoothing than with the standard smoothing values.

In examining the results in table 3, it is seen that there were considerable differences, ranging from about 30 to 400 seconds, in performance between the mean warning times in the various scenarios even though a 120-second position prediction was used in all cases. Thus, a 120-second position prediction did not necessarily result in a 120-second warning of hazardous situations because the actual warning time also depended on the scenarios being used.

The other aspect of tracking and Conflict Alert algorithm performance of interest was the negative, which is when nuisance, or false, alerts are generated. Such an alert is one that would not have been generated if the current true position and velocity of the targets under observation had been known. In such cases, the true target trajectories do not violate the separation standards. The largest single factor in the generation of nuisance alerts is the tracking lag in heading, illustrated in figure 9, which occurs as a target turns. Performance data for the analysis of nuisance alerts were obtained for the three scenarios given in figure 8.

The quantitative measure of nuisance alert performance was based on the maximum value of the probability of an alert, using tracks that start at locations that do not yield alerts if true position and velocity are known. Since there is a region of considerable size in which nuisance alerts may be generated, some approach had to be divised to summarize the performance in this region. The technique developed was to sample the performance of the Conflict Alert algorithm over the entire area of possible nuisance alerts. At each sample point (position), the maximum probability of an alert occurring when tracks are initiated at that point was weighted by an appropriate area in which the simulation results could be assumed constant, yielding a single performance statistic for each scenario. This statistic was defined as the nuisance alert area (in nmi^2) the equivalent area of nuisance alerts for each maneuver detection and smoothing parameter combination. The implication in the use of this performance measure was that if targets were assumed to have been uniformly distributed throughout the coverage area of the sensor, changes in the nuisance alert area would result in similar changes in the false alarm rate.

The results of the nuisance alert area simulations were given in table 9 of section 3.4. None of the maneuver detection options or smoothing parameters values were uniformly optimum in all cases, thus making a choice between the various combinations extremely difficult. The performance variation in the nuisance alert area between the maneuver detection options were not considered particularly significant, but there was considerable significance in the difference between the results for the standard smoothing parameters and those obtained with the track-oriented smoothing parameters.

In the case of scenarios 1 and 3 at 480-knots, the track-oriented smoothing results showed a substantial improvement in performance as compared to the standard smoothing parameters, while in the case of scenario 3 at 220 knots, the results showed a marginally significant improvement in the nuisance alert area using track-oriented smoothing. In the case of scenario 2, however, the use of track-oriented smoothing resulted in a substantial increase in the size of the nuisance alert area except in the case of the dynamic search area with a one-scan delay. Clearly, the use of track-oriented smoothing was the major cause of the performance differences observed, but the contradictory nature of the results makes any selection process extremely difficult.

In order to combine the results from each simulation into one overall figure of merit, a system of weighting factors can be devised for each scenario. Considering each case in table 9 as equally significant, the results obtained with the track-oriented smoothing parameters and the dynamic search area with delay provided the best results, although their differences from the other maneuver detection options were for practical purposes insignificant. Weighting factors can also be determined based on flight rules or a random distribution of headings. However, all approaches involve assumptions that may not be valid in an operational environment. For this reason, the use of any assumption to develop weighting factors was rejected.

For an example of the potential danger in making such assumptions, suppose that the operational environment for a particular region has a far higher proportion of situations corresponding to scenario 2 than was assumed in the weighting factor analysis. In such a case, the number of nuisance alerts may actually increase as a result of the use of track-oriented smoothing with any maneuver detection option, with the possible exception of the dynamic search area with one scan delay. As a result, it is concluded that the only maneuver detection option that could be used with track-oriented smoothing with only a limited potential for significant increases in the nuisance alert area is the dynamic search area with delay. This conclusion is reached despite the fact that the combination of the MTD with the dynamic search area, each with a one-scan delay, gave a slightly lower overall nuisance alert area.

The reason for the increase in the nuisance alert area for scenario 2 was thought to be due to the substantial increase in the speed and heading errors for straight-line tracks, as illustrated in table 10, which accompanied the use of track-oriented smoothing. The increase was substantially lower however, in the case of the dynamic search area with a one-scan delay. The increase in the speed and heading errors, due to the erroneous application of the large search area smoothing constants on straight-line tracks, is a penalty that must be accepted in order to use track-oriented smoothing.

Since the most significant impact on the nuisance alert area performance is due to the use of track oriented smoothing rather than the particular maneuver detection option under consideration, another factor that entered into the selection process was the relative ease of implementation of the various maneuver detection options. Therefore, another reason for choosing the dynamic search area with a one-scan delay over the MTD plus dynamic search area, other than the relatively insignificant performance differences and the substantial increase in the speed and heading errors, was the fact that the use of the MTD data would still require a fair amount of computational resources despite the simplistic approach

that was taken. Software would be required to format and transmit the SIN's and also to process the data as it is received. It would also be necessary to store the MTD data for use in the threshold comparison process and this would require additional storage amounting to one-half word per track.

For the dynamic search area with a one-scan delay, the computational resources required are minimal and the programming necessary to perform the basic search area computation has already been developed for a previous study (reference 16). Implementation of the one scan delay would require additional storage of only one bit per track. While the increase in the speed jitter using the dynamic search area with a one-scan delay might be operationally acceptable, the significantly larger increase associated with the MTD would certainly not. Additional processing of the velocity information would be required to smooth or "sanitize" the speed for display purposes, thus increasing the computational requirements even more. The use of track-oriented smoothing is simply a parameter change and would result in no additional computational or storage requirements.

The fact remained that the combination of the MTD and the dynamic search area did, in some cases, result in better nuisance alert area performance than the dynamic search area alone. The question arose as to whether or not other changes could be made in the tracking and Conflict Alert algorithms that could duplicate the performance improvement obtained using the MTD data but without the penalty of increased computational resources or the additional speed and heading errors.

A natural approach in this case was to reduce the size of the alert generation region. This modification was made and the results were given in tables 11 and 12 for scenario 3. As these results show, the nuisance alert area performance of the conflict alert algorithm is extremely sensitive to changes in the size of the alert generation region. For scenario 3 of (220 knots, with the standard smoothing parameters), the nuisance alert areas were reduced by more than an order of magnitude and those at 480 knots were reduced by a factor of approximately 3. In fact, with this change in parameter values for the alert generation region, the results for the standard smoothing parameters were better than the results for track-oriented smoothing regardless of the maneuver detection option chosen. The specific change made in this case was to reduce the value of the SPMB and SPPB parameters from 4.8 to 2.8 nmi. While such a substantial reduction may not be operationally acceptable, it did indicate an extreme sensitivity to changes in these parameter values.

Smaller reductions in the SPMB and SPPB parameters combination with the dynamic search area with delay, plus more moderate track-oriented smoothing parameters should be able to duplicate any performance improvements obtained using the MTD in combination with the dynamic search area. Using this alternative approach would avoid the additional computational resources needed to process the MTD data and would also mitigate the increase in the speed and heading errors. The reduction of the size of the alert generation region might be expected to lead to a reduction in the warning time but as the results in table 10 show, the reductions found in this case were judged insignificant according to the criterion used previously.

As a result, it is concluded that there is no justification for using the SIN's provided by the MTD in the present operational system, because the performance improvements that could be obtained using this data can be duplicated by far simpler modifications and parameter changes in the system. This conclusion applies only to the present operational system and was derived using an optimistic value for the errors in the SIN's. If field results do not equal or exceed the assumed errors, then the conclusion is even more justified.

The attempt to use the radial velocity MTD data in the present system is just another example of the futility of attempting to introduce additional features into a system whose performance of original function has not yet been optimized. As was noted in the previous study (reference 5), "... the evaluation of the use of the MTD data cannot be divorced from a consideration of the dynamic search area and the general problem of parameter optimization."

As previously stated, the results and conclusions discussed above apply only the computationally limited environment of the present system using position measurement provided by the Air Traffic Control Radar Beacon System. Efforts are currently underway to develop a new radar, Mode S, which will have significantly improved accuracy and a higher data rate, and to procure a new air traffic control computer (the 9020 replacement). The question now arises as to how the results and conclusions of this study would apply in an environment with virtually no significant restrictions on computational resources and with more accurate radar data.

Under such conditions, the use of a more sophisticated tracking algorithm should result in improved tracking performance. This, in turn, would result in better detection of maneuvers, as the data will be more accurate and will provide earlier detection of the bias resulting from a maneuvering target. The need then for the MTD as a maneuver detector would be questionable therefore, because the tracking performance should improve as a result of the new data and tracking algorithm. In any case, the technique that was used in this study, that is, the use of a threshold with the MTD data for maneuver detection, is an approach that should only be used in situations in which the computational resources are extremely limited. Since this will not be the case in the future, the approach in this study will not be applicable then: obvious alternatives will exist which should provide even better performance.

If it is desired that maneuver detection be performed in the future, an approach that could be taken would be to develop an adaptive maneuver detector in which the radial velocity is computed from the smoothed velocity calculated by the tracking algorithm. Estimated SIN's could then be computed and compared to the measured values, the difference in turn being compared to an adaptive threshold computed by tracking the difference between the measured and calculated values. Since the calculated values would be based on the assumption of a constant velocity straight-line trajectory, large differences would be taken as an indication of a maneuvering target.

Another approach that would be feasible is to use the SIN's to compute an estimate of the radial velocity based on the MTD measurements. Since tracking algorithms can be developed that take vector measurements and use each component according to a weighting factor derived from measurement accuracy, any additional information can be used. If the accuracy is poor, however, little weight will be given to the information.

Presently, the major unsolved problem in the design of tracking algorithms is the determination of the best technique for maneuver detection. Previous studies have already shown the significant performance improvements that can be achieved using a data link for transmission of maneuver information (references 25 through 27), but this approach was not considered in this report. For targets without a data link, the MTD-derived data could be used to supplement the performance of the Mode S tracking algorithm, but since the tracking algorithm for use with the Mode S sensor and the new air traffic control computer has not yet been designed, it is unknown whether the performance will actually require any enhancement.

Consequently, it is concluded that the need for the MTD data in the case of the new computer using Mode S cannot be determined at the present time. It should only be considered if the accuracy of the MTD data is sufficient to provide a measurement of the radial velocity of the target, and then only if the use of the data link to provide turning information has been rejected.

5. RECOMMENDATIONS.

The results of this study show that using the Speed Interpolation Numbers (SIN's) from the Moving Target Detector (MTD) for maneuver detection in the present operational environment of limited computational resources yields an insignificant improvement achievable as well through simple changes in the tracking parameters. Parameter changes were, in fact, found to be of far greater overall importance than the type of maneuver detection used. It is recommended, therefore, that the SIN's not be considered for such use. However, in a future operational environment not subject to limitations on computational resources, such as one consisting of Mode S or with the advanced replacement computer, alternative algorithms that use the radial velocity information could be considered.

It is recommended that if further consideration is given to the use of the SIN's for maneuver detection, the characteristics of the data to be available in the operational environment should first be analyzed to determine the feasibility of using them to compute the radial velocity of targets. It is also recommended that operational performance data on the Conflict Alert algorithm be used to assess the relative significance of the scenarios used for the tracking simulations.

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